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Photoelastic residual stress measurement in non-axisymmetric glass containers

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Abstract. Residual stresses in axisymmetric glass containers are mostly measured with integrated photoelasticity. However, many containers, e.g. cosmetic bottles and bottles of expensive alcoholic drinks, often have a non-axisymmetric form. In this paper we consider residual stress measurement in such containers with a modified integrated photoelasticity technique, with the scattered light method and with a simple method of surface stress measurement.

1 Introduction

Residual stress is one of the most important characteristics of glass articles from the point of view of their strength and resistance. For about a century, photoelasticity has been the most widely used method for quality control in the glass industry. Stresses in glass articles of axisymmetric shape (bottles, drinking glasses, tubes, fibres and fibre preforms, electric lamps) are mostly determined with integrated photoelasticity [1,2].

Many containers have non-axisymmetric form. Determination of 3D stress fields in general in these articles requires application of photoelastic tomography [3,4]. However, in thin-walled objects tomography is usually not efficient.

This paper considers the application of integrated photoelasticity, a simple method of surface stress measurement [5], a scattered light method [6-8] and a simplified photoelastic tomography for the determination of stresses in non-axisymmetric containers. Several examples are provided.

2 Integrated photoelasticity

In integrated photoelasticity the test object is placed in an immersion tank. The ruler test[1] is used to mix the immersion liquid such that its refractive index matches that of the specimen. A beam of polarized light is passed through the specimen (Figure 1a). The light rays which pass the axisymmetric hollow glass article parallel to the midsurface, between points *A* and *B*, are the most informative. This is named illumination by tangential incidence.

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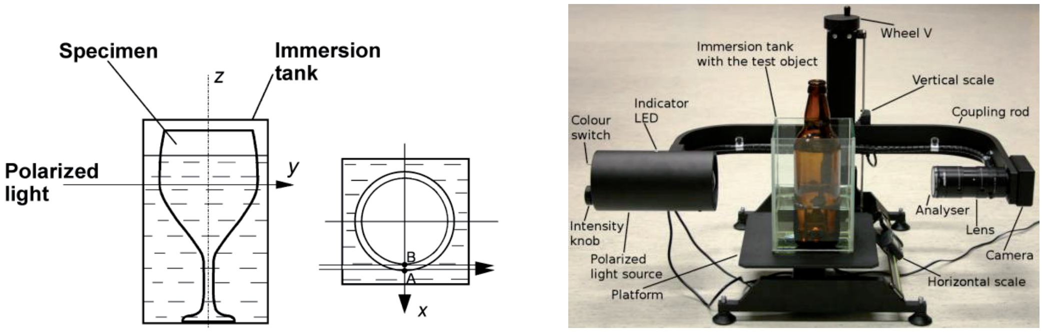


(a) (b)

Fig. 1. Measurement scheme of integrated photoelasticity (a) and transmission polariscope AP-07 (b). The polariscope is manufactured by GlasStress Ltd.

Transformation of the polarization of light in the specimen is measured on many light rays with a computer-controlled polariscope (Figure 1b). The polariscope permits measurements of optical retardation and parameter of the isoclinic with the phase-stepping method [9]. As the values and directions of the principal stresses vary on the light rays, optical phenomena in integrated photoelasticity are non-linear and the relationships between the measurement data and parameters of the stress distribution are non-linear, too. However, it has been shown [2, 10] that if birefringence is weak or rotation of the principal stress directions on the light rays is weak, a 3D specimen can be investigated in a conventional transmission polariscope similar to 2D specimens. On every light ray it is possible to determine the parameter of the isoclinic φ and the optical retardation δ. The latter are related to the components of the stress tensor on the ray by the simple integral relationships

$$\delta \cos 2\varphi = C\int (\sigma_z - \sigma_x)\mathrm{d}y\,,\ \delta \sin 2\varphi = C\int \tau_{zx}\mathrm{d}y \tag{1}$$

where C is the photoelastic constant, and σ_x, σ_z and τ_{zx} are components of the stress tensor in the plane perpendicular to the light ray y. Equations (1) are valid if either optical retardation is less than one-third of the wavelength or rotation of the principal stress along the light ray is less than $\pi/6$ [10]. If no rotation of the principal stress axes is present, Equations (1) are always valid.

It has been shown that if the parameter of the isoclinic φ and the optical retardation δ have been measured on many light rays in two parallel sections, perpendicular to the axis z of the axisymmetric specimen, then radial distribution of the axial stress σ_z and the shear stress τ_{rz} can be determined [2]. Using the equilibrium equation and the sum rule, the radial stress σ_r and the circumferential stress σ_θ can be determined [11,12].

3 Surface stress measurement at the corners

Methods have been developed for determining the stresses at the corners of the test object [5]. The polarized light is passed obliquely through the test object in the direction of the ξ axis as shown in Figure 2. It has been shown that the normal stress σ_y at the corner A of the edge can be calculated as follows

$$\sigma_y(A) = \lim_{\zeta \to 0} \frac{\delta(\zeta)}{Cl(\zeta)}\,. \tag{2}$$

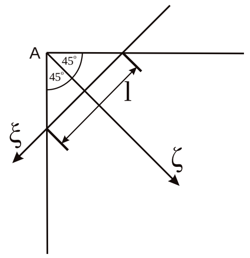


Fig. 2. Passing light obliquely through the specimen near the corner. The *y* axis is normal to the plane defined by the ζ and ξ axis.

Optical retardation $\delta(\zeta)$ should be measured near the corner at different distances ζ from the latter. On the basis of the measurement data the curve $\delta(\zeta)/\ Cl(\zeta)$ can be constructed. Extrapolation of this curve to the corner gives the value of $\sigma_y(A)$.

Let us note that this method is applicable to corners of any convex form.

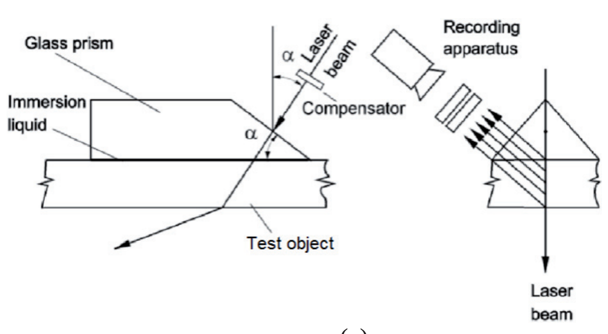
4 The scattered light method

If a laser beam passes through a glass object, the light is scattered in the plane, perpendicular to the direction of the beam. The intensity of the scattered light depends on the birefringence caused by the stresses. This opens up the possibility to measure the distribution of the residual stresses through the thickness of glass objects [6-8].

Figure 3a shows the scattered light measurement scheme. A laser beam is directed into the test object perpendicularly to an inclined surface of a glass prism to avoid refraction of the light. Usually the angle α is equal to 45º. A thin layer of immersion liquid between the prism and the test object improves the optical contact.

Because of stresses, the polarization of the laser beam varies when it passes through the test object. Variation of the polarization also means variation of the intensity of the scattered light. The latter is recorded with the video camera and based on this measurement data the stress profile in the test object is calculated. Both components of the principal stresses can be determined when measurements are carried out in the directions of both principal stresses. Figure 3b shows a photograph of a portable scattered light polariscope SCALP-04, manufactured by GlasStress Ltd.

Although the polariscope was elaborated bearing in mind residual stress measurement in flat glass panels, it can be used also for the measurements in glass articles of arbitrary shape in parts, which are sufficiently flat. Practice has shown that a viscous immersion liquid is required to enable measurements on convex surfaces where it would easily flow away otherwise.



(a) (b)

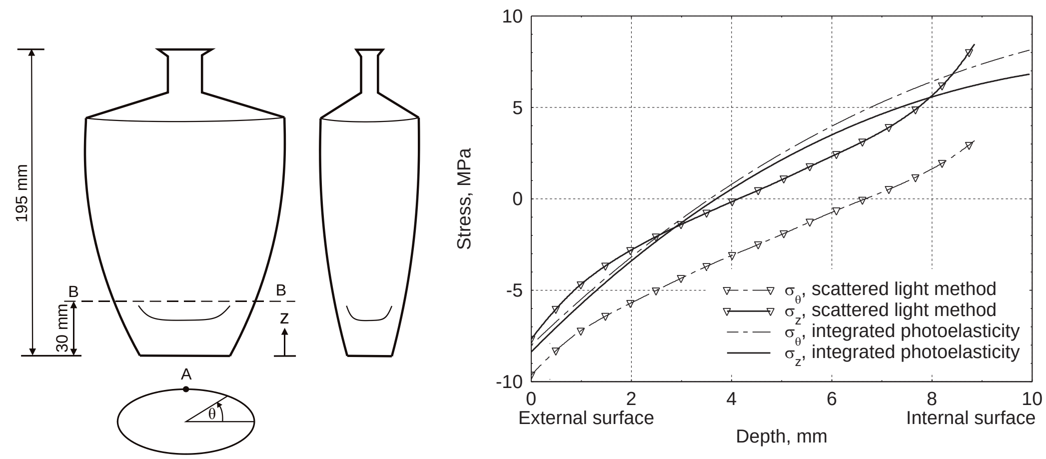
Fig. 3. Scattered light measurement scheme (a) and the polariscope SCALP-04 measuring stress in a bottle (b).

5 Examples

5.1 An elliptical bottle

The bottle, shown in Figure 4a, has almost flat side surfaces. At the point *A*, stress distribution through the thickness was determined by both integrated photoelasticity, using local radius of the curvature for the specimen radius and the scattered light method. The results, shown in Figure 5b, show good agreement for the axial stresses.

In addition, the axial stress at the surface around the perimeter was determined using the surface stress measurement method. Results are shown in Figure 5.



(a) (b)

Fig. 4. Geometry of the elliptical bottle (a) and stress distribution through the wall at the point *A* in section *B-B* (b).

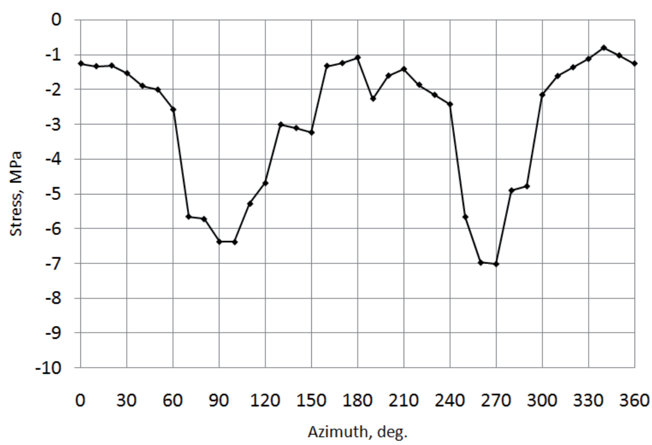
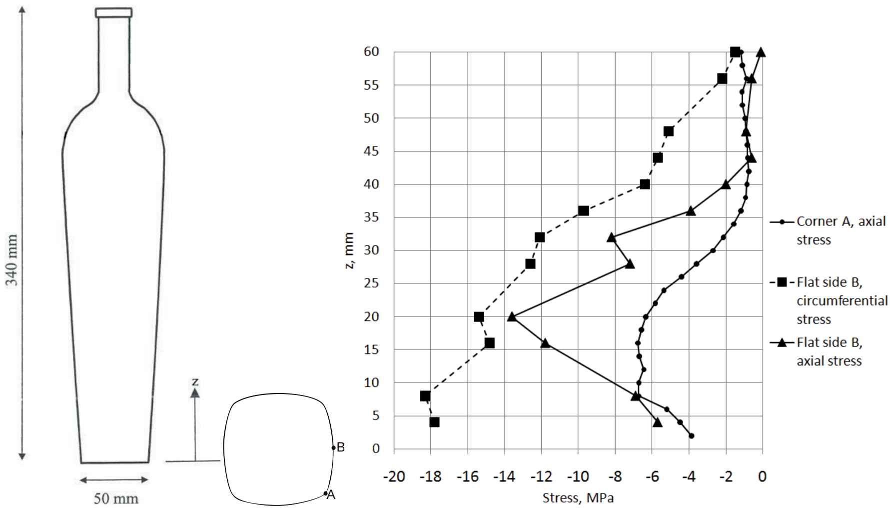


Fig. 5. Distribution of axial stress at the external surface around the perimeter in section *B-B*.

The surface stress measurement gives -6.5 MPa for the axial stress at the surface at the point *A* in section *B-B*. This is in good agreement with the results for axial stresses shown in Figure 4b. However, the circumferential stresses, determined with integrated photoelasticity differ significantly from those determined with the scattered light method. A possible explanation for this is the invalidity of the assumptation that sum rule [12] can be used for determing the circumferential stress component even when the specimen is not axisymmetric. Let us mention that in the scattered light method, both principal stresses are determined with the same precision.

5.2 A bottle of square cross-section

The geometry of the bottle is shown in Figure 6a. Axial stresses at the corner *A* were determined using the surface stress measurement method. Axial and circumferential stresses at the flat side *B* were determined using the scattered light method. Results are shown in Figure 6b.



(a) (b) (c)

Fig. 6. Geometry of the bottle (a), cross-section at the heel (b) and distribution of stresses at the corner *A* and on the flat side *B* near the heel (c).

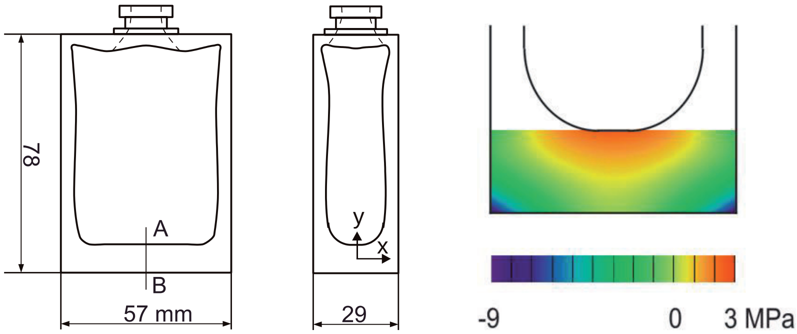
The axial stress component approaches zero at the heel as expected. However, it is interesting to note that the circumferential stress component at the flat side *B* is the biggest one.

5.3 A cosmetic bottle

Geometry of the cosmetic bottle is shown in Figure 7a. Photoelastic measurements were made by scanning the section *xy* in three directions, in the direction of the *x* axis and and at ±45º with it. Normal stress distribution in the section *AB* was approximated with polynomial in the following form:

$$\sigma = c_0 + c_1 x^2 + c_2 y + c_3 y^2 + c_4 x^2 y + c_5 x^2 y^2 , \tag{3}$$

where the constants $c_0 ... c_5$ were determined with the least squares method. In essence this is a simplified version of photoelastic tomography [3,4]. The color-coded stress field is shown in Figure 7b.



(a) (b)

Fig. 7. Geometry of the cosmetic bottle (a) and normal stress field in the section *AB* (b).

6 Conclusions

It has been shown that integrated photoelasticity, the scattered light method, a simple method of surface stress measurement and a simplified version of photoelastic tomography can be used to determine stresses in non-axisymmetric containers. Comparision of the results of different methods shows a rather good agreement.

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