Automatic Fracture Photoelastic Analysis of a Tempered Thick Glass Plate

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ABSTRACT

The photoelastic method was used to measure the residual stresses existing in selected areas of a cabin door that are considered critical in the failure of the same door. The technique was applied to samples taken from a door that was broken to obtain samples. Of the total measured samples, the average residual stresses was measure.

For comparison purpose, the obtained values of residual stresses were compared with the values related to flat glass windows in transportation vehicles. The residual stresses are important in determining the modulus of rupture of the glass. The higher the residual stresses are, the higher the modulus of rupture of the glass is.

1. INTRODUCTION

As well known, glass is a typical example of brittle materials. In many products made of glass, such as a front glass of car or a glass of a tractor door, high compressive residual stresses are often induced artificially at its surface to avoid incidental fracture and damages.

Fracture of glass takes place by crack propagation under tensile stresses.

Any condition or treatment which induces compressive stresses on the surface of the glass, will make the glass stronger. In order to reach this goal, two basic techniques can be used: thermal tempering and chemical tempering. In thermal tempering the glass is first heated near the softening point, and then rapidly cooled by applying a stream of air.

The temperature gradient in the material and the difference between the coefficients of thermal expansion at the surface and inside the glass, cause the outer layers to be subjected to compression. The induced stresses depend on the plate thickness. In chemical tempering, a surface compression is developed by ion implantation.

The value of the induced compression stress depends on the tempering technique used, glass composition and thickness of the glass. In both cases the induced state of stresses takes the shape indicated in Figure 1.

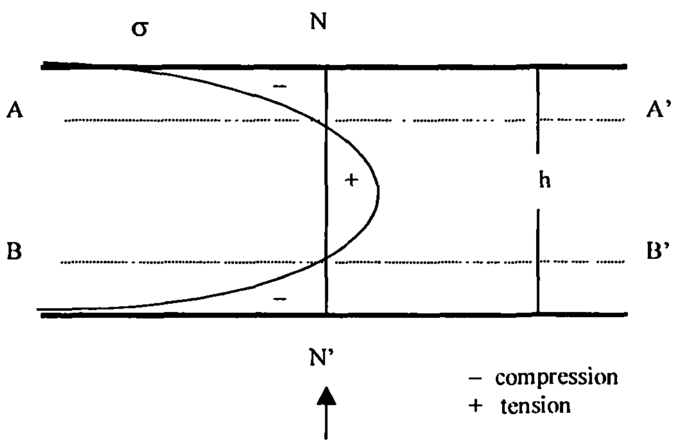

Fig. 1: Residual stress in a tempered glass

The lines AX and BB' are lines of zero stress. The lines AA' and BB' are lines of zero stress. The maximum compressive residual stress occurs at the external boundaries, inside the lines of zero stresses the glass is subjected to tension. The value of the induced compression stress depends on the tempering technique used, glass composition and thickness of the glass. There is a direct relationship between the modulus of rupture of the tempered glass and the temper stress. The modulus of the rupture can be presented by the approximate relationship:

modulus of rupture = basic strength of the glass + induced compressive stresses

The stress patterns in stressed glass can be visualized by means of photoelasticity. Photoelastic patterns provide the difference of the principal stresses at the point under observation. However, proper understanding of what is being observed is required to relate the patterns to the degree of tempering. If one looks in the direction perpendicular to the glass surface, one sees an integrated effect. In air tempering the two principal stresses are not equal, and looking on the direction perpendicular to the glass surface, one can see some optical retardation. There is not a simple relationship between the values one can measure by normal observation and the state of stress.

In flat glass, differential surface refractometers can be used to measure surface residual stresses. These instruments are based on the difference between the refractive indices for rays polarized parallel and.

perpendicular to the glass surface. Another technique that can be used is scattered light photoelasticity. All of the above described methods are nondestructive techniques, meaning that one can measure the stress differences in the actual part without cutting it. Looking through the thickness, which implies cutting the glass, one can measure the principal secondary stresses in the plane of observation. Since the stress component perpendicular to the face of the glass plate is negligible, one measures directly the stresses induced by the tempering. In the case of chemical tempering, an isotropic state of stresses is created, therefore the stresses in all possible orientations are the same, except at the edges of the glass. In the case of air tempering the stresses may be different in different planes, that is, there are two principal stresses which are the maximum and minimum stresses. Consequently, measuring residual stresses at an arbitrary orientation, one will obtain values in between the maximum and the minimum. Since the glass fragments coming from the broken window can be used as slices, one can perform measurements of residual stresses in them. This is the procedure that was selected to determine the presence of residual stresses in the fragments coming from a broken window.

2. APPARATUS AND EXPERIMENTAL PROCEDURES

To perform the measurement of the residual stresses, computer assisted photoelasticity was applied. Figure 2 shows a schematic representation of the setup.

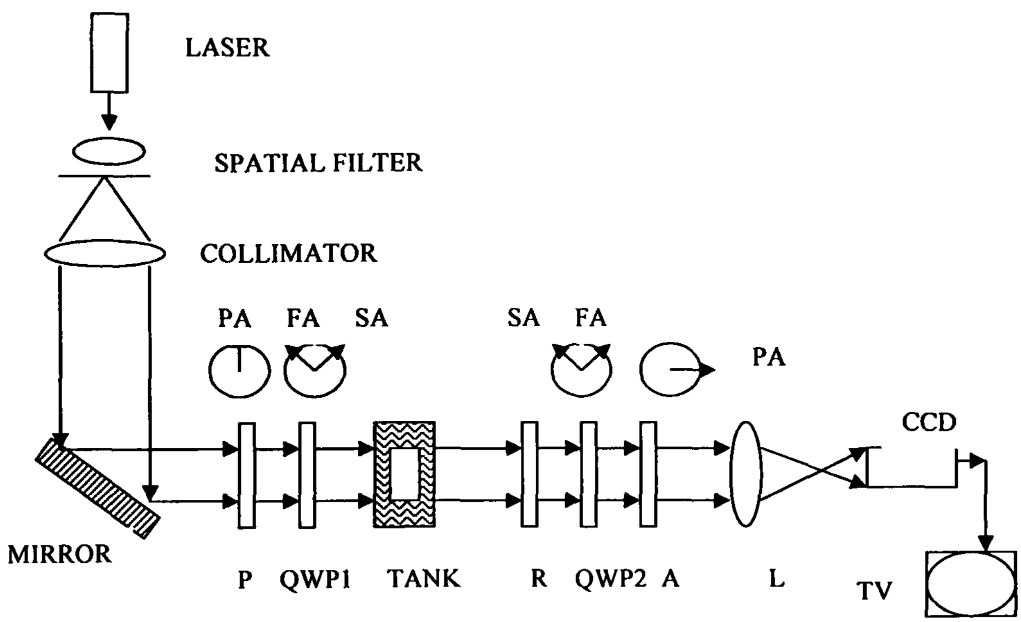

Fig. 2: Schematic representation of a photoelastic set-up

The photoelastic image is captured by a CCD camera /1/, /2/, /3/, /4/. The information is digitized by a digital to analog converter. The digitized photoelastic pattern is processed by a combination of hardware and software that yield accurate values of the retardation to three significant figures. The photoelastic fringes (fig. 3) are analyzed as spatially frequency modulated two-dimensional signals. The utilized software retrieves the phase information of the fringes.

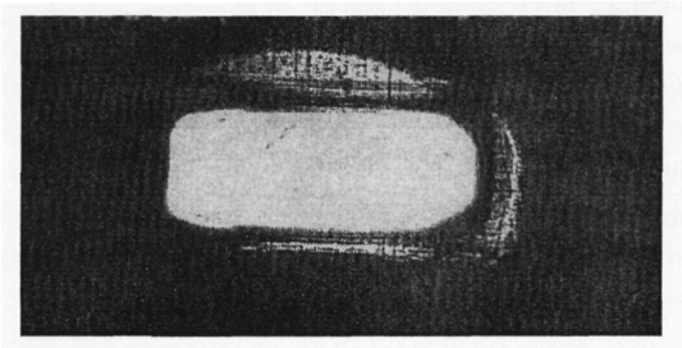

Fig. 3: Fringe pattern of the residual stresses of a piece taken from the external edge of the door.

Values of retardation are determined at each pixel of the image, in the present case 401 points. The maximum residual stresses are located at the surface. Since the surface is a transition between two media, there are edge effects that disrupt the photoelastic measurement. The customary procedure in photoelasticity is to use extrapolating polynomials to determine the edge values. In the case of residual stresses in glass, careful analysis of a large sample of data show that the residual stress distribution can be accurately fitted by a four order polynomial. To compute the values at the edges of the glass four order polynomials were used. These polynomials are defined by the total number of measured points and therefore the extrapolated values carry the weight of all the measured values, thus providing extremely accurate results. To convert the measured retardation values to stresses, the photoelastic constant C= 1600 lbs/sq.in./in. was used, which is an average value for plate glass.

The observed glass fragments were immersed in an index of refraction matching fluid. In this way it was insured that the correct optical path was followed by the light beams

To get representative values of the residual stresses for each one of the window panels whenever possible, three samples were analyzed from the center of the panel and three samples from the edges. Since the residual stresses induced by thermal tempering are not isotropic, reading at several orientations give a better average than a single sample. Furthermore one will expect that at the edges the residual stresses will be smaller.

Ten samples were taken from a frame identified as "Glass Frame with Glass Fragments and one Bag of Glass Fragments ", this frame will be called broken window.

Figure 4 shows the region of the door that was analyzed. In Figure 5, a not to scale plot of the different locations is reported with the coding representing each analyzed slice (framed number) and the distances (number without frame).

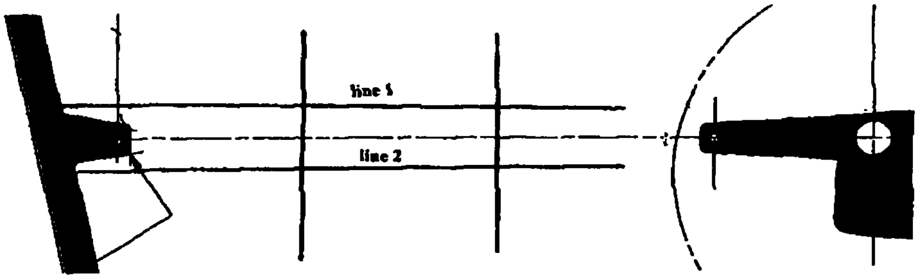

Fig. 4: Area of interest (door handle)

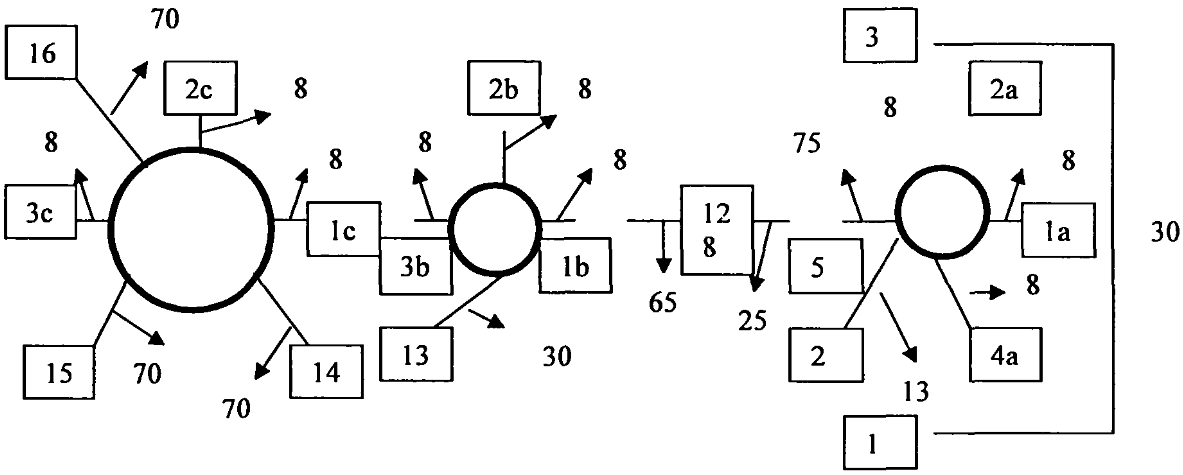

Fig. 5: Map of the analyzed pieces with numbers and distance (mm) from the handle holes.

3. RESULTS

We collected a large number of pieces, but due to the irregularities of the fracture surface many samples had to be rejected since they did not give consistent readings. We have also mentioned the fact that since the failures of the glass are random, the measured stresses may not correspond to the maximum or minimum stresses at the point under consideration. On the twenty samples that we performed measurements on, only five have good surfaces in perpendicular directions. Figures 6 and 7 show the plots of the residual stresses of the different slices.

The plots have two curves, one represents the measured retardations and the other the interpolating four order polynomial. One can see that there is an excellent agreement between the values given by the polynomial and the measured values. Table I shows the corresponding results.

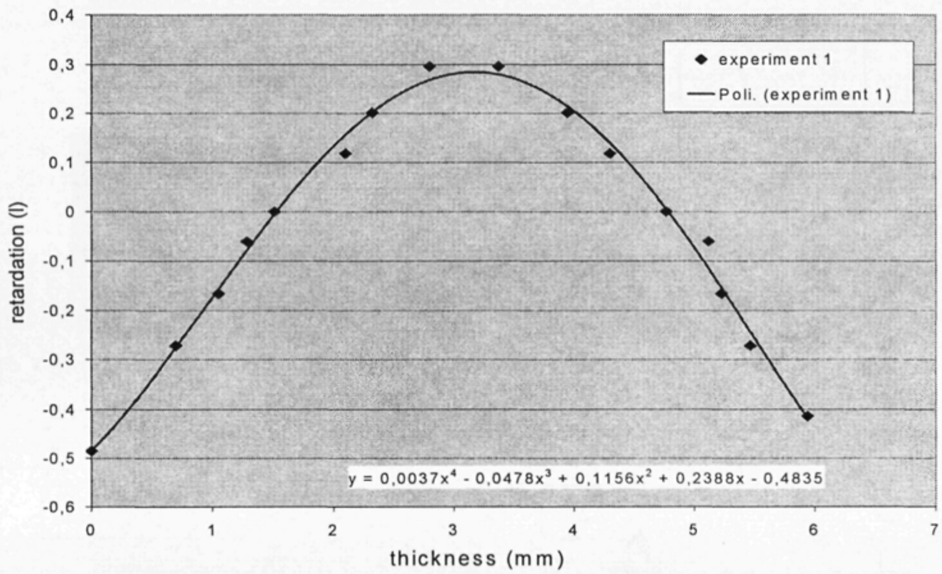

Fig. 6: Graphs of retardation vs depth (specimen 1)

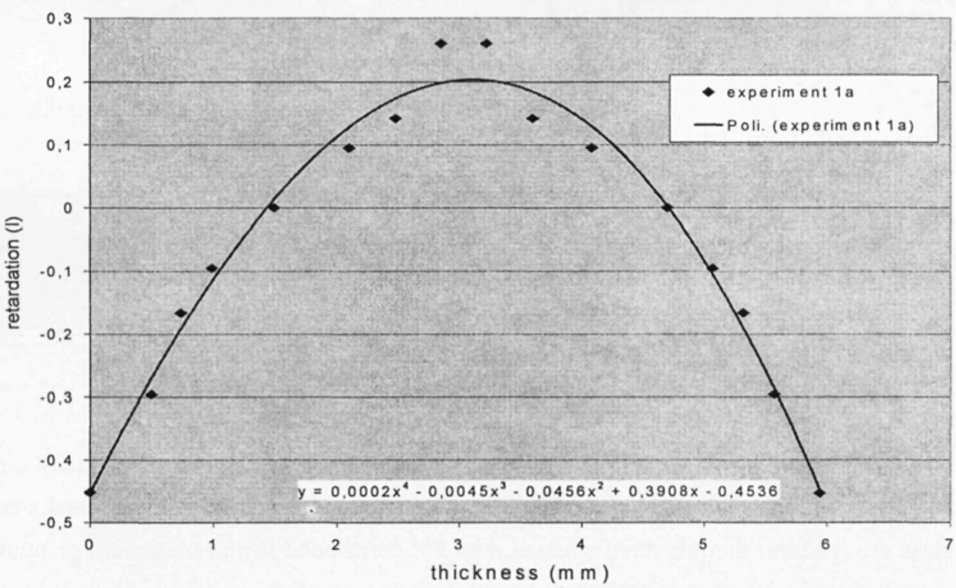

Fig. 7: Graphs of retardation vs depth (specimen 1a)

Some of the slices have symmetric distribution while others are asymmetric.

Table I:
Average maximum compressive stress for the different slices

Specimen code	Stress (psi)	Specimen code	Stress (psi)
1	12.877	3c	17.779
1a	12.785	4a	13.360
1b	12.763	4c	14.394
1c	12.295	5	12.851
2	17.385	8	14.369
2a	13.606	12	11.459
2b	12.365	13	12.285
2c	17.365	14	14.827
3	13.625	15	15.440
3b	12.080	16	17.280

5. CONCLUSION

From the measured values one can conclude that the broken window /5/ has been subjected to thermal tempering. The residual stresses introduced by thermal tempering, vary from 13,000 to 20,000 lbs/sq.in. depending on the kind of glass, thickness and air tempering unit. The values that we have measured go from 12,758 to 16,002 lbs/sq.in. which are well within the statistical dispersion that one would expect if one takes random samples with random orientation. We can conclude than the automatic system used in this measurements gives a vary good result and can be easily applied for any kind of photoelastic test.

6. REFERENCES

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