Residual Stress Measurement of Automobile Windshields Using The Grey-field Polariscope

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1.0 Introduction

Automobile windshields have had to evolve rapidly in order to keep pace with the innovative body styles of today's newer automobiles. Windshields have become larger for increased visibility, are sloped at greater angles for improved wind resistance, and are shaped with more pronounced contours than ever before. Manufacturing the newer windshield shapes with the appropriate residual stress levels has become an increasingly difficult problem. An instrument that can efficiently and accurately measure residual stress in windshield glass is needed. The Grey-field Polariscope [1], [2] provides a reliable, full-field measurement of the residual stresses in the windshield, and has demonstrated excellent repeatability, an attribute that many competing instruments lack.

In order to prevent cracks from forming at the edge of windshields a compressive stress is manufactured into the windshield glass at the edge along the perimeter of the windshield. A residual tensile stress is created adjacent to the compressive region, which must neither exceed a specified magnitude nor extend too far into the center of the windshield. If the residual stresses in a windshield exceed the specified limits, then the added stress of installation or normal wear and tear could cause premature failure and lead to costly warranty repairs. Quantifying the edge compressive stress and the adjacent residual tensile stress before the windshield is installed into a vehicle is a critical step in preventing failures.

2.0 Grey-field Photoelasticity

A detailed explanation of the Grey-field Polariscope is contained within the first two papers listed in the references section. A brief summary of the technique and the instrument will be given here as background to facilitate a discussion of the windshield data and analysis. In most traditional photoelastic techniques [3] two sets of circular polarizers are used to measure stress or strain in an object (like glass) or a photoelastic coating. The Grey-field Polariscope uses a polarizer and quarter waveplate to project circularly polarized light, but only a single rotating polarizer, or analyzer, positioned just before the RGB camera to interpret the returning light intensity (figure 1).

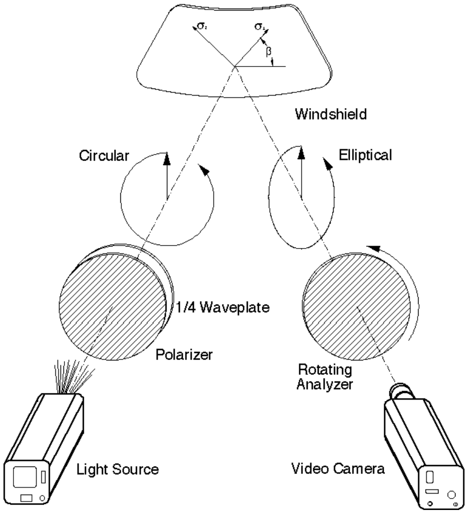

Figure 1. Grey-field Polariscope components

The circularly polarized light is transformed into elipticaly polarized light by the birefringence in the glass. Instead of converting the elliptical light back into a linear form with a second quarter waveplate, and making the traditional measurement of the realtive retardation between the two vectors which define the elipse, several images are collected at defined angles during the rotation of the analyzer. The intensity of the light is measured at each analyzer position during the rotation, beginning with a reference position at time t=0.

$$I = \frac{a^2}{2}\left[1 + \sin 2(\omega t - \beta)\sin\Delta\right] \qquad (1)$$

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[1] Stress Photonics Inc., 3002 Progress Road, Madison, WI 53716
[2] Daimler-Chrysler Corp., 800 Chrysler Drive, Auburn Hills, MI 48326-2757
[3] General Motors Corp., 30001 Van Dyke 2-10., Warren, MI 48090

With no birefringence (_ = 0) the returned signal is a grey value instead of the black or white that would be returned from a traditional polariscope. A video lock-in technique is used to average images together for multiple revolutions of the analyzer improving sigal to noise. The position of the analyzer is monitored so that a full-field measurement of the direction of the first principal stress or strain is also made. Images of the residual stresses in the glass along the 45 degree (e.g. figure 5) and zero degree (horizontal) shear plains are used to create an image of the maximum in-plane shear, which can be interrogated using a profile plot feature of the software (e.g. figure 4). The birefringence values obtained from the profile plot are then converted into units of stress by the process described in section five of this paper.

3.0 Testing Procedure

Windshields selected for testing were first cleaned and then prepared with a reflective, silver backing on the number four (inside) surface of the windshield along the edge. The black paint band or fritting normally located on the inside surface of the windshield had not been applied in order to use the silver spray paint, which is a better reflector. Ongoing experiments using the black fritting as the reflector have shown that it is adequate for acquiring data even though the amount of usable light is significantly reduced. Once the silver paint has dried the windshield is placed on a stand in a stress free state and inspected using the Grey-field Polariscope. The compressive stress was great enough at all locations so as to exceed the subfringe limit of the system, resulting in multiple fringe images of the edge compressive stress. In order to resolve the compressive fringes a 17mm macro lens was used to collect the images. Data sets were acquired in about one minute, and stored for analysis after acquisition was completed. Each image represents approximately 6.35cm^2 of windshield area.

4.0 Results

For the purpose of this paper results from a single automobile windshield will be reported, although measurements have been made on several windshields from different types of vehicles. Residual stress measurements for nineteen preselected locations on the windshield are presented in Table 1. Images of the four corners were also collected and analyzed, because interesting patterns in the stress were noticed. A diagram marking the approximate location of each measurement point on the windshield follows (figure 2). A windshield thickness of 5.4mm was used in the calculation of the stress values. A windshield of this type that meets specifications has an minimum compressive stress of 10.3MPa, an average tensile stress no greater than 5.2MPa, and a maximum tensile stress no greater than 6.9MPa.

Table 1: Residual stress measurements from an automobile windshield

Location Number (see figure 2)	Edge Compression (MPa)	Residual Tension (MPa)
1	16.05	4.01
2	20.70	4.01
3	16.52	2.25
4	15.38	1.92
5	12.04	2.56
6	20.06	7.05
7	17.29	6.92
8	17.43	6.23
9	18.10	6.18
10	15.17	4.14
11	16.05	5.47
12	14.09	4.01
13	9.02	3.07
14	14.20	4.01
15	15.57	2.74
16	10.24	1.99
17	10.14	2.34
18	12.04	3.83
19	12.04	4.10
13/19 corner	17.33	2.83
14/9 corner	18.56	4.17
1/6 corner	5.43	3.34
5/10 corner	6.52	2.68
Average (1-19)	**14.90**	**4.05**
Maximum (1-19)	**20.70**	**7.05**

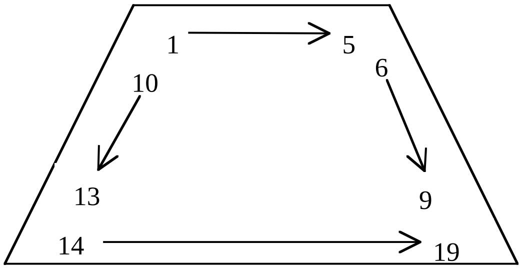

Figure 2. Approximate location on the windshield of each measurement reported in Table 1.

5.0 Analyzing Windshield Data

Understanding the interpretation of the data requires some knowledge of traditional photoelastic techniques.

One of the goals of developing a windshield inspection system is to incorporate image interpretation and analysis algorithms into the software, so that the process is automated, and interpreting the data is not strictly limited to engineers with some background in photoelasticity. At this time that goal has not been achieved, so the following discussion should help in understanding and interpreting the data.

A stress pattern resulting from residual stresses at the edge of a windshield has a characteristic shape (figure 3) highlighted by a compressive peak, a transition into tension, and a broader tensile peak, which falls off to zero stress towards the center of the windshield. In this case, the peak values are within the subfringe range of the system, so there are no fringes to count and the values correspond directly to stress in the windshield.

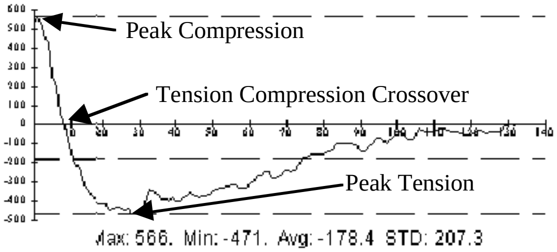

Figure 3. Characteristic distribution of residual stresses at the edge of a windshield with magnitude less that the _ wave peak stress.

Once the stress values in the glass exceed a certain limit, which for the Grey-field Polariscope is one quarter of a wavelength of birefringence, a fringe pattern develops in the images (figure 4), which must then be interpreted in order to determine stress values. At the edge of a windshield the compressive stress usually exceeds the _-wave limit, and instead of one continuous peak, multiple peaks of alternating sign appear.

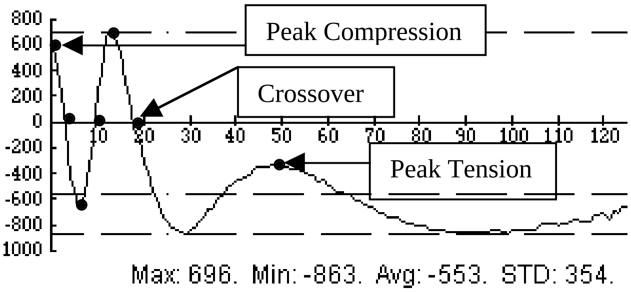

Figure 4. Profile plot showing the stress pattern from location #6 where the magnitude exceeds the _ wave peak stress.

The process for calculating the compressive stress for the plot in figure 4 would be to first identify the tension /compression crossover. From the tensile peak, which occurs farther from the edge than the compressive peak, follow the plot to the left. The first zero crossing is the transition from tension into compression. The peak compressive stress should be the greatest positive value, except that the _-wave limit is reached and surpassed, which forces a direction or sign change in the signal. The next zero crossing is not interpreted as a transition from compression into tension, but rather as a second sign change indicating that _-wave has been generated. The _-wave value is indicated by the next peak, and the whole wavelength value is achieved with the last zero crossing. The plot terminates at a value of approximately 600, which is just at the 1_ peak value, so that the final fringe value (N) used to calculate the stress value is 1.25. The equation used to convert the values provided by the Grey-field Polariscope into birefringence values is

$$N = \frac{\sin^{-1}\left(\frac{value}{peak}\right)}{360} \tag{2}$$

where value is obtained from the image. Peak is the maximum value for 1/4 fringe, and N is the calculated fringe order. Knowing the wavelength of the light used for the inspection (450nm in this case) and the birefringence coefficient (2.2psi in/nm for float glass), the units can be converted into units of stress.

The image in figure 5 depicts the multiple fringe pattern observed along the 45 degree shear planes at the edge of the windshield at location #6. The edge compressive region is defined using the profile plot (figure 4), or by observing the location of the crossover fringe using a RGB three color technique. 650nm (red) and 550nm (green) wavelengths of light were used at selected locations as a means of spot checking the procedure.

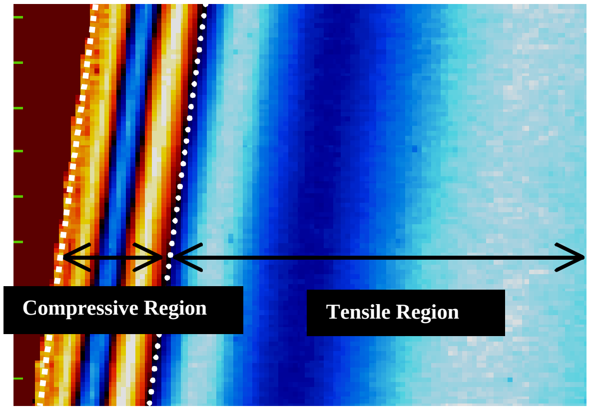

Figure 5. Image showing the compressive and tensile residual stresses along the 45 degree shear planes at location #6.

5.0 Application of RGB Photoelasticity

Collecting data with three different wavelengths of light (e.g. red, green, and blue) provides additional information that can help in distinguishing between actual features in the glass (e.g. a tension/compression crossover) and wavelength related features (e.g. a 1/4-wave peak). Actual features of the glass will appear in the same location for each separate wavelength image, whereas wavelength dependent features will be in different locations depending on the wavelength of light used. Using multiple wavelengths will also eliminate the problem of diminished resolution at the _-wave peak. A shorter wavelength of light will reach the _-wave limit before a longer one, so that while one wavelength is reporting at a low resolution peak (e.g. _, _, and so on) the other(s) will be reporting data from a linear (high resolution) region. Using multiple wavelengths will always ensure that the highest resolution data is accessible.

For applications where the residual stresses far exceed those found in windshields, for example tempered glass, three color photoelasticity becomes almost essential [4]. The stress pattern is less predictable than in windshields especially at locations away from an edge, which can often aid in understanding the stresses. In such an instance, a three color technique is necessary in order to locate the zero crossing.

6.0 Conclusion

Two locations on this windshield exceeded the specified limit for tensile stress, but only slightly. Locations six and seven were (22psi) and (3psi), respectively, over the 6.9MPa (1,000psi) limit for tension. All other stress results were within specified limits.

More experience measuring residual stress in windshields will help in the development of a windshield inspection device specifically designed for the task, rather than the current configuration which is intended for component inspection using photoelastic coatings. High resolution optics (e.g. a 17mm lens) and shorter wavelength light (e.g. 450nm) is necessary to properly inspect the compressive edge stress. On the contrary, a wider field-of-view is often necessary in order to see the entire tensile region.

This technique has proven to be very accurate, repeatable, and operator independent, for the measurement of residual stress in windshield glass. Developments that will greatly improve the usefulness of the system include incorporating a RGB algorithm into the software that will automate much of the analysis, and configuring a fixed focal length, hand held system specificly designed for measuring the residual stresses at the edge of windshields.

References

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[2] Lesniak, J. R., Zickel, M. J., Welch, C. S., Johnson, D. F., “An Innovative Polariscope for Photoelastic Stress Analysis,” Proceedings of the 1997 SEM Spring Conference on Experimental Mechanics, Bellevue, WA, June 2-4, 1997, 219-224.

[3] Dally, J. W., and Riley, W. F., Experimental Stress Analysis, Third edition, McGraw Hill, Boston, MA, 1991, pp. 429-440.

[4] Lesniak, J. R., Zickel, M. J., Bazile, D. J., Boyce, B. R., “Assessment of Grey-Field Photoelasticity,” to be published in the Proceedings of the 1999 SEM Spring Conference on Experimental Mechanics, Cincinnati, OH, June 7-9, 1999.