# Applications of modern automated photoelasticity to industrial problems

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*The very latest advances in modern photoelastic analysis techniques now offer the opportunity to carry out real-time stress monitoring of components or structures. No more time-consuming complex coating applications, no more time consuming manual reading of fringes - a simply applied, quick cure coating and a fully automated polariscope system linked to a high speed CCD camera can monitor changing stress patterns as they happen. The old, time-consuming, high skill requirement, photoelastic technique is finally bought up to date and offers a unique efficient full-field dynamic stress analysis method. This paper highlights the advantages of automated photoelastic stress analysis with examples of its use and introduces a new dynamic photoelastic system and the wide potential for its further use.*

Keywords: Photoelasticity, stress analysis, real time stress monitoring, dynamic applications, quality control, inspection.

## Introduction

Various automatic photoelastic systems have been developed over the last 10-15 years, but not until the advent of the Stress Photonics Inc Grey-Field Polariscope (GFP) 1000[1] has the technique been simple enough to use routinely in an engineering test laboratory environment. With easier-to-apply photo-reflective coatings, it is now a relatively quick and simple task to take a complex part and determine the stress distribution under a variety of loading conditions. The technique can also be used for determining assembly stresses, due to bolt-up loads or interference fits and the like, and has also found particular use as a quality monitoring tool in the glass industry[2].

Previously, all the above applications required either inherent residual stresses (as in glass), or static incremental loading. However, the latest generation of the GFP technology from Stress Photonics now offers true *real*-time analysis and, for the first time, true *dynamic* photoelastic analysis capabilities. The two techniques are described briefly in this paper, along with examples of applications and the potential for the future involving Rapid Prototype (RP)[3] models.

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## Description of GFP 1000

The layout of the GFP is shown in Figure 1 and consists of a projector unit delivering circularly polarised light and a CCD camera with a constantly rotating analyser. For each revolution of the analyser a number of images are captured which allow the intensity of the reflected light to be measured. The returning polarised light, if there is stress causing birefringence present, is elliptical, and from this intensity data it is possible to calculate the axes of the ellipse and its angle of retardation. From this the captured image can be expressed as defined by a Mohrs circle solution representing shear stresses in vertical and horizontal planes, together with the maximum shear stress:

| | |
|---|---|
| $\sigma_x - \sigma_y$ | (Figure 2 shows Shear 45 output in a hole in a plate specimen) |
| $\sigma_{-45} - \sigma_{+45}$ | (Figure 3 shows Shear 0) |
| $\sigma_1 - \sigma_2$ | (Figure 4 shows Shear max output) |

In the past, when carrying out work with reflective coatings, several fringes needed to be observed in order to make accurate measurements. As the number of fringes is proportional to the thickness of the coating (see below) thicker coatings (typically 3-4 mm) were used to obtain multiple fringe orders.

$$\sigma_1 - \sigma_2 = \frac{nf}{t}$$

where: $\sigma_1$ = Max principal stress
$\sigma_2$ = Min principal stress
n = Measured fringe order
f = Material fringe coefficient (determined by calibration)
t = Thickness of coating

The greatest advance with the GFP is not just in its ease of use but also, due to the extreme sensitivity of the equipment, in its ability to accurately measure fractions of a fringe order. Due to this enhanced sensitivity, up to a maximum of ± 0.002 fringe, much thinner coatings can be used to produce sufficient birefringence for successful photo-reflective analysis. This has resulted in the simplification of the coating procedure. It is now possible to brush on epoxy resin coatings with a thickness of between 0.1-0.4 mm, taking only a few minutes to prepare and just a few hours to fully cure. There is the potential now for a complete analysis of a simple component or structure to be done in less than a day!

## Examples of GFP 1000 applications

One of the main uses for the instrument (Figure 5) has been in the glass industry, both for architectural and automotive applications. Previously, measurements were made manually using hand-held polariscopes and just gave point measurements. With the advent of the GFP, full-field measurements can be made very quickly over fairly large areas of glass. Automotive laminated windscreens, for

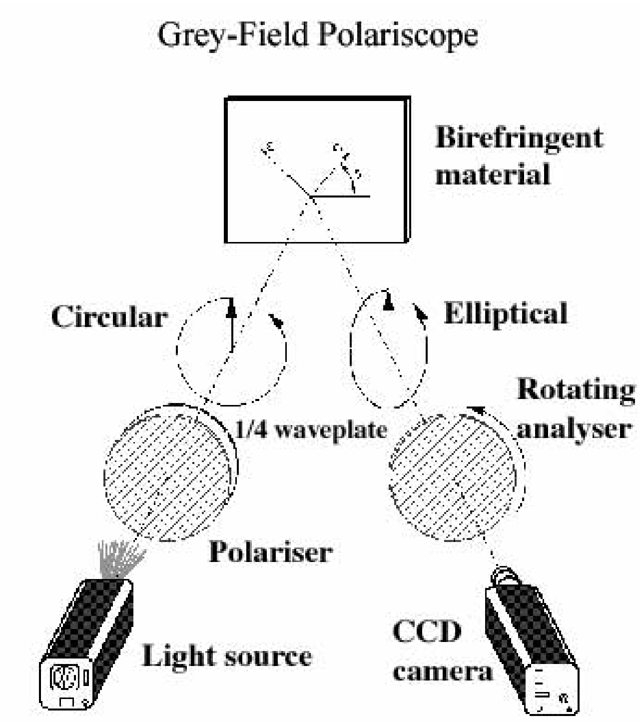


Figure 1. Diagram of GFP 1000 method of operation

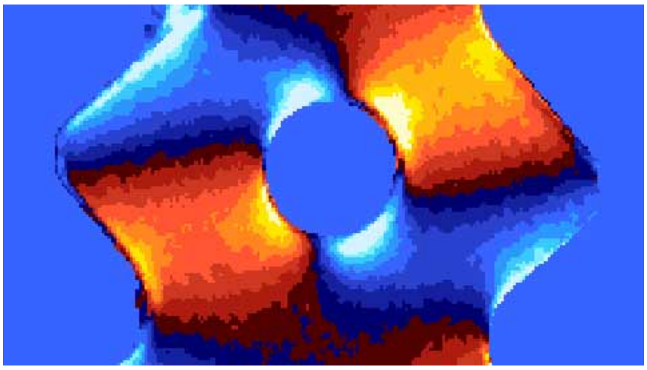

Figure 2. Shear 45 image

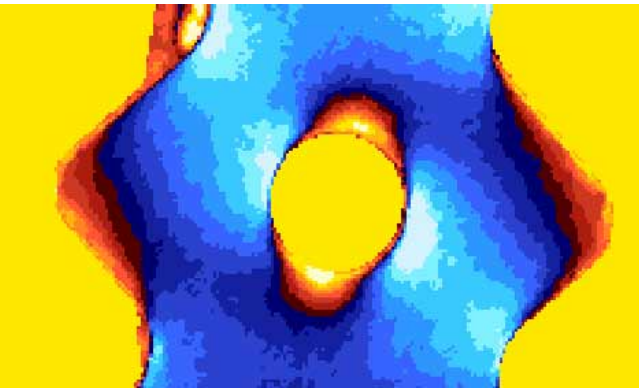

Figure 3. Shear 0 image

example, must have a significant compressive edge stress to prevent crack generation and propagation, hence failure (see Figures 6 and 7). Nowadays, all windscreens have a black obscuration band around the edge, not only to cover the adhesive bond for aesthetic reasons, but also to prevent ultra-violet light from degrading the adhesive. With conventional polariscopes this band, which is heated and bonded into the glass, would have to be removed - ordinarily by abrasion - in order to measure edge stresses, sometimes removing some of the glass and scraping the windscreen in the process. However, such is the sensitivity of the GFP that sufficient light can be reflected off the black surround to measure edge stresses (Figure 8) without destroying the screen, making it useable for on-line inspection.

Toughened glass also can be quickly inspected using the GFP and again, due to the larger field of view, the whole glass area can be inspected very quickly. From these images any problems due to blocked cooling jets, uneven heating and residual stresses around holes can be monitored. An example is shown in Figures 9 and 10. Figure 9 shows a normal tempering pattern and Figure 10 shows an anomaly on the right-hand edge, which could cause problems in terms of early crack prorogation etc. So, for the glass manufacturer the GFP 1000 is an excellent quality monitoring tool, enabling close checks to be made on their furnace parameters, machining and handling processes.

Glass problems within the automotive industry are not only down to manufacturing processes. Present trends are to fit larger screens and stylish bonded wrap-around finishers, all of which start to contribute to overall vehicle stiffness. Vehicle-induced stresses

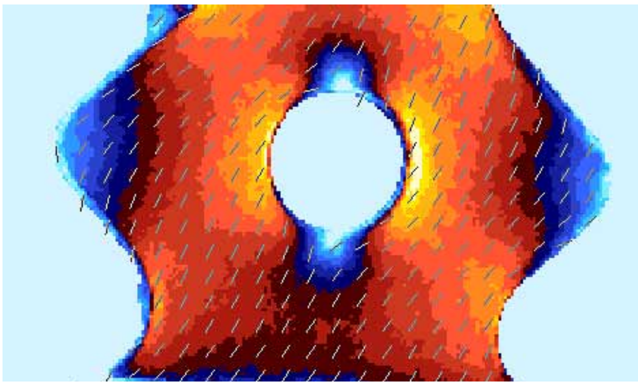

Figure 4. Shear max image

Figure 5. GFP 1000 Equipment set-up

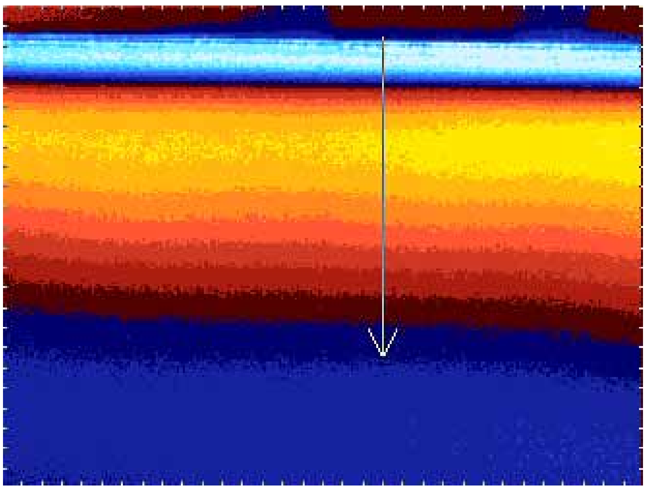

Figure 6. Glass edge stress image

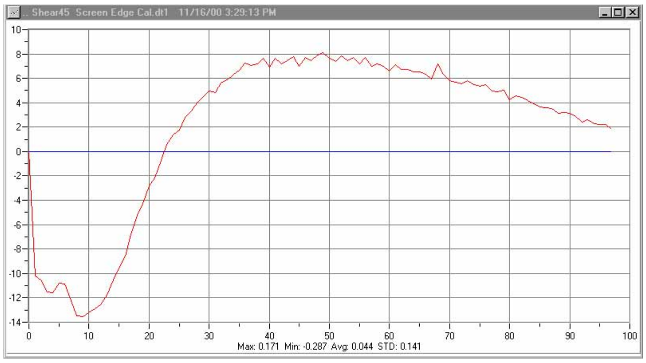


**Figure 7 Glass edge stress plot**

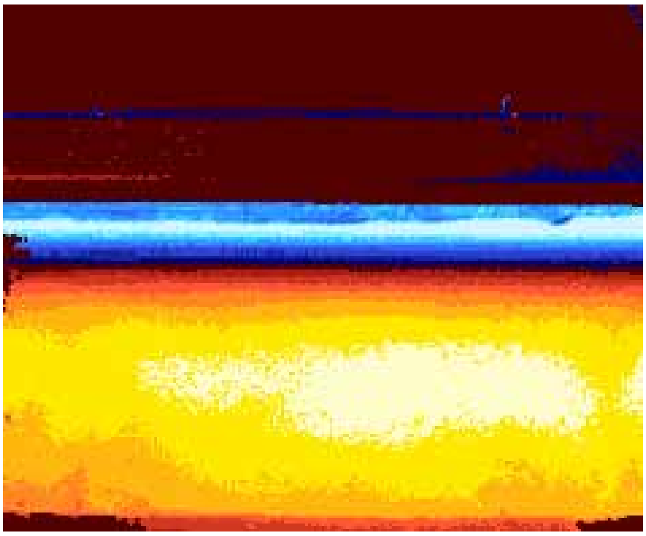

**Figure 8. Glass edge stress off black frite**

and assembly stresses, for example fitting of pneumatic tailgate lifters direct to the glass, have the potential to cause premature failure. This can now be quantified by applying photoreflective coatings direct to the glass surface and monitoring the stresses using the GFP during loading. Figure 11 shows the stress concentrations generated due to the tightening of a fixing bolt through a hole in the glass.

The photoreflective coating technique coupled with the GFP can also be used to good effect on metallic structures. The software allows subtractions to be made of assembly or residual stresses, so that only the effect of the relevant loading can be observed. A degree of motion compensation is available; if, for example, during a static incremental loading the object deflects within the field of view slightly (10-20 mm), a re-alignment feature is available in the software to correct for this. For determining load paths and stress concentrations, the technique is extremely efficient and effective, as shown in Figure 12, in this case stress concentrations around a rivet. Designers can check out their finite element predictions or locate strain gauge positions for load transducers very quickly. The new fast cure resin can be brushed on in a thin layer (typically 0.25 mm thick) and the GFP used to obtain images over the whole area. Standard optical lenses can be used to allow for wide angle or macro, close-up requirements.

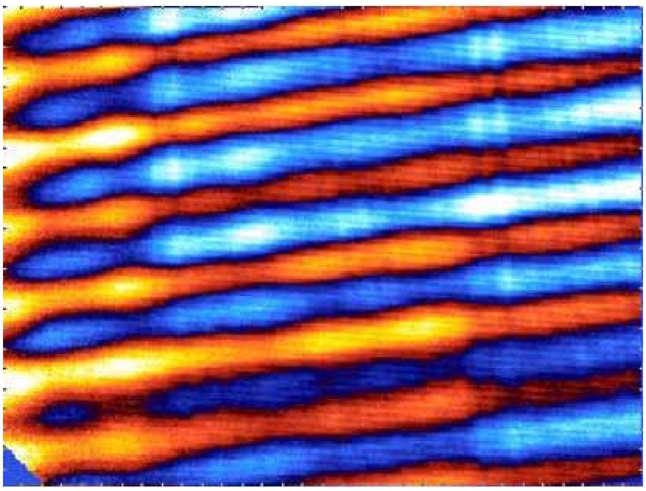

**Figure 9 Toughened glass image**

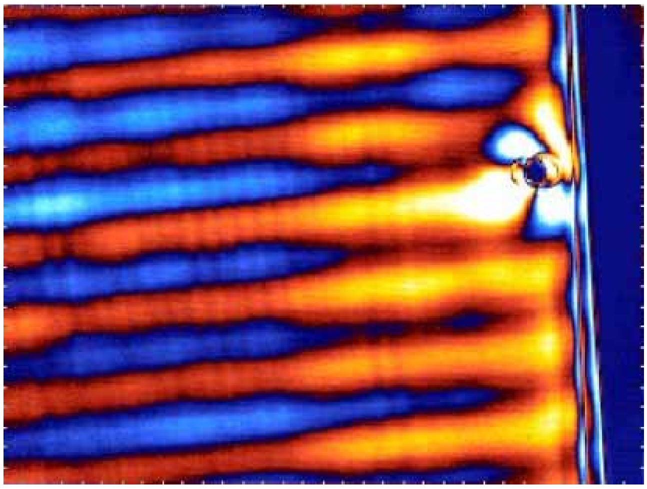

**Figure 10. Toughened glass image with anomaly on edge**

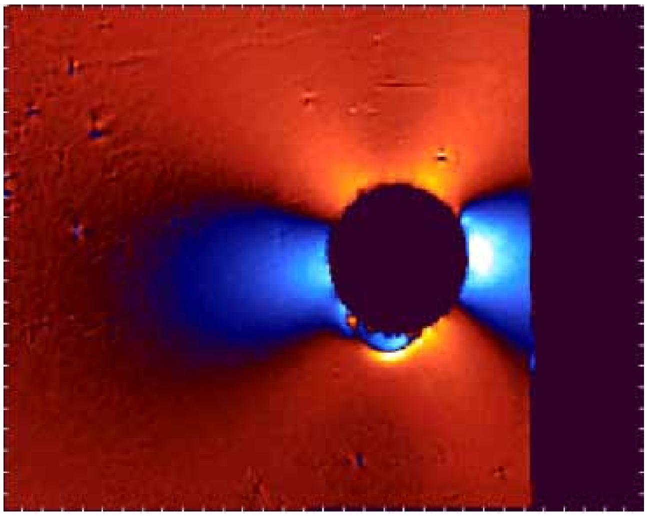

**Figure 11. Tail gate hatch mounts**

## Real-time photoelasticity

A combination of work by Sheffield University[4,5], initially using four cameras and a recent, extremely innovative, compact lens arrangement from Stress Photonics[6], has now made real-time photoelasticity a reality. The GFP 2000 (Figure 13) brings a new dimension to automated photoelasticity. It is lightweight and compact, allowing it to be positioned in awkward places or even mounted direct on to structures being subjected to dynamic loadings. The technology has only just become commercially available, so examples are limited but the potential is widespread.

For the glass industry it opens up on-line quality inspection capabilities and the software allows real-time observation of the edge stresses as the glass is passed in front of the camera. Figure 14 shows a typical output from the new system, with the real-time image moving on the left and the graph being generated, also in real time on the right. Failure parameters can be set up within the software in order to 'flash' up a warning if stress levels fall out of the required specification.

The dynamic ability allows a greater understanding to be obtained of the way contact stresses interact or load paths alter with shifts in angular loading. Using high-speed cameras the potential to investigate impact situations can be realised. The new fast cure coating permits greater areas to be coated and the versatility of the GFP 2000 will open up still further applications.

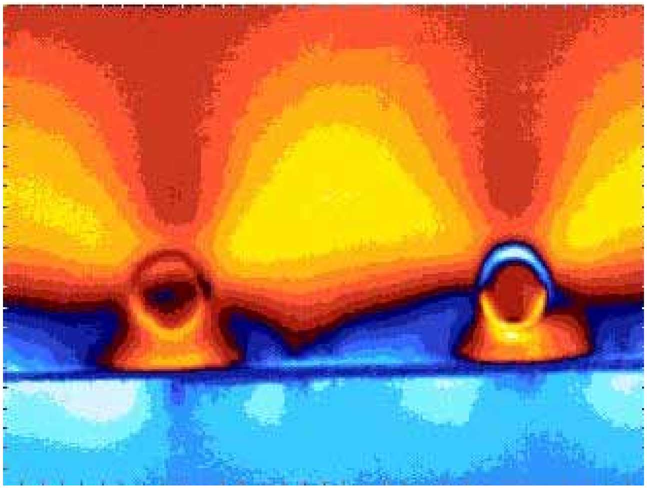

**Figure 12. Stress concentrations around rivets**

**Figure 13. The GFP 2000**

## Future developments

The next innovation for photoelasticity will be in the coating material. Firstly, spray-on coatings will become available, making the coating procedure even more simplistic. Other materials have potential, from space-age polymers back to old materials previously abandoned due to their lack of sensitivity. Already, work has shown that transparent anodised coatings are sufficiently birefringent for the GFP to detect stress patterns (Figure 15), a technique particularly useful for crack growth monitoring, even in harsh high-temperature environments.

The use of RP models for analysis at the concept stage of design has been demonstrated before[7] but technology such as real-time photoelasticity opens up more potential for this type

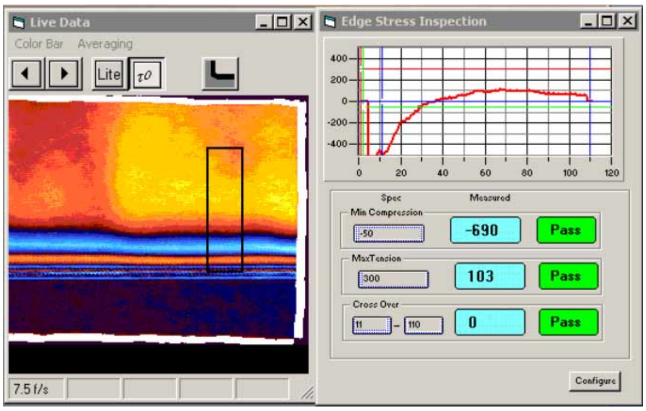


**Figure 14. GFP 2000 output**

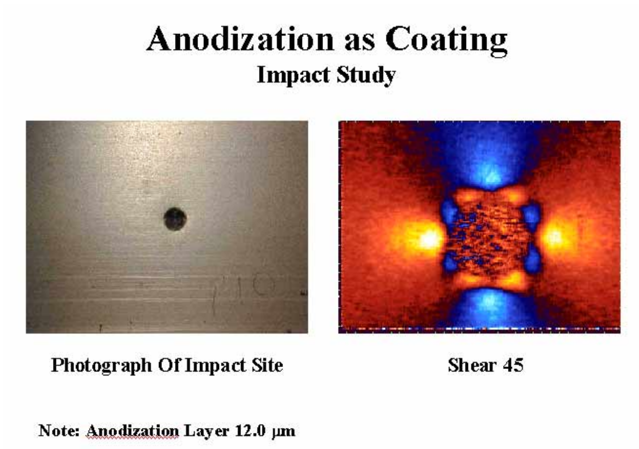


**Figure 15. Birefringence from anodised coatings**

of activity. Work is ongoing to modernise and simplify the three-dimensional photoelastic technique, using RP models and a tomography approach to separate photoelastic fringes prior to analysis with the GFP. The value for ultra-fast validation of a designs integrity should not be underestimated and the technology described here will be a valuable asset for future designers where cost and time reduction becomes an overriding priority.

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