

Shearography - in identifying the presence and subsequent measurement of Residual stresses.

By Jasson Gryzagoridis¹, Dirk Findeis², Tendai Chipanga¹

Department of Mechanical Engineering

Cape Peninsula University of Technology¹, University of Cape Town², South Africa

Phone: +27 21 6503229

Fax: +27 21 6503240

E-mail: jasson.gryzagoridis@uct.ac.za

Abstract

Residual stresses are known to influence the performance of components in structures usually in a detrimental/damaging manner, however sometimes their presence can be advantageous, especially if they are compressive, thus inhibiting fatigue failure. It is recognized that residual stresses are induced during manufacturing processes and as such they are uncontrolled and unknown. This paper deals with the feasibility study of using Digital Shearography to identify the presence of Residual Stresses and subsequently quantify them. Experiments were performed on mild steel rectangular bars where a compressive residual stress was introduced in one of the surfaces of the specimens. The results are encouraging in that Digital Shearography could be developed as a residual stress measuring tool thus prompting further parametric studies. The testing method also appears to yield the value of the Young's modulus of the material.

1.0 Introduction

Residual stresses may be defined as stresses that exist within a small layer underneath the surface of a structural material in the absence of any external loads. They arise as a consequence of almost the entire range of manufacturing processes of components and are thus uncontrollable. The fact that residual stresses are also self equilibrating makes them difficult to detect and measure. It is widely recognized that residual stresses alter the design performance of a structural component, usually in a detrimental manner hastening its failure; however there are instances where the presence of residual stresses in a structural component is advantageous. For example a compressive residual stress would be beneficial to components prone to fatigue failure or stress corrosion cracking, Ruud¹. Modern engineering practice focuses on optimization and as such, aims to reduce mass and size of components with the end result the reduction of safety factors in design, consequently the estimation of residual stresses can no longer be overly conservative. The demand for accurate, preferably non-destructive testing measurements of residual stresses is increasing, but in practice we must infer to the residual stress value by observing or

measuring a secondary quantity, such as displacement, strain, the speed of sound, magnetic field etc, Withers et al.².

The techniques for measuring residual stresses can be classified into three categories depending whether they are destructive non destructive or emerging methods which could be either of the former two, but have yet to be widely accepted as standardized techniques. Examples of destructive methods of measurement are block-sectioning, layer removal and even hole drilling, all relying on the relief of stress, by removal of material. A non-destructive alternative would be X-ray diffraction while ultrasonic velocity and Barkhausen noise analysis (the latter for ferromagnetic materials only) would be classified as emerging techniques mostly restricted to laboratory use.

Optical NDT techniques like holographic interferometry and electronic speckle pattern interferometry have been applied to measure residual stresses in the past, Gryzagoridis³. Digital Shearography, currently enjoying considerable success as a laser based NDT technique, was originally presented as a strain measurement technique, and being truly a non-destructive non-contacting full field measurement method, its applicability to measure residual stress might be advantageous. This paper presents a feasibility study of utilizing the technique of Digital Shearography as a method of measuring residual stresses.

1.1 Digital Shearography

Typical laboratory Digital Shearographic systems, similar to the one depicted in fig. 1, include personal computers housing software to process the images of the object under test. A single wavelength light source (a laser) is used to illuminate the object and produce the required speckled image, Gryzagoridis et al.⁴.

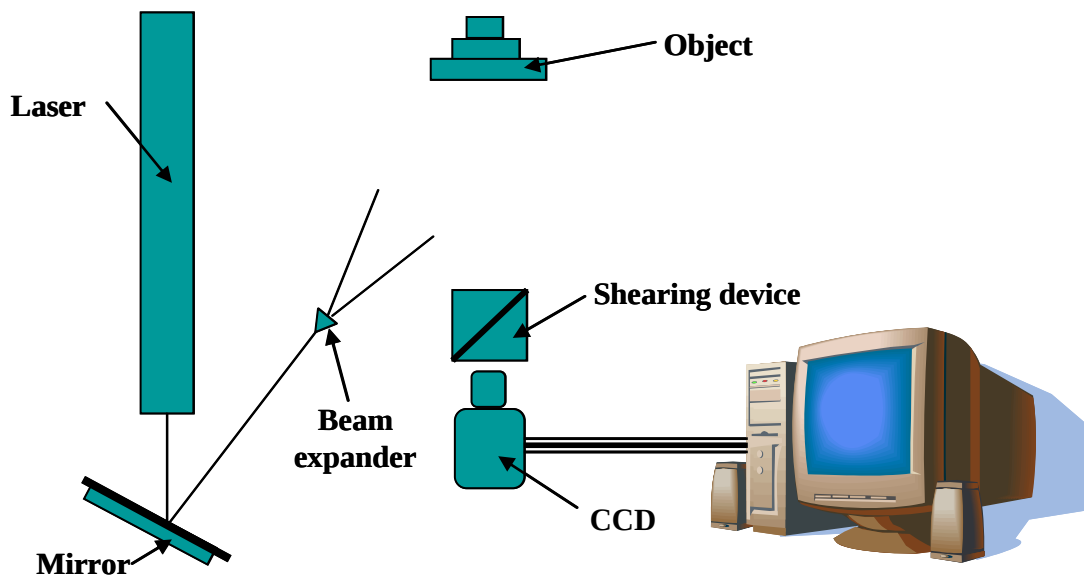


Figure 1. Typical laboratory Shearographic system

The behaviour of the surface of the object under test can be observed by a simple procedure at real or almost real time conditions. The images are obtained via a digital camera viewing the object through some adjustable shearing optics and are stored in the image digitizer. An image of the object stored in the computer is compared to another image of the object obtained after the object has been perturbed say for instance by the application of a small force. The result of the comparison of the two images is a pattern of dark bands, known as fringes, superimposed on the image of the object. The fringes are lines of constant gradients or the slope of out-of-plane surface displacements quantifiable by the following expression

$$\frac{\partial \delta p}{\partial x} = \frac{\lambda N}{2S} \quad (1)$$

In the equation above λ is the wave length of the laser, N is the number of fringes observed, and S is the image shear imposed. Clearly the sensitivity of the measurements depends on the magnitude of image shear S .

The choice of the type of specimen and its geometry to carry out the feasibility study of Digital Shearography as a technique to identify and quantify residual stresses, was based on the desire to introduce rather easily residual stress in the specimens as well as the ability to predict mathematically the behaviour of the specimen under load. For these reasons it was decided to conduct the experiments using rectangular mild steel bars fashioned as cantilever beams loaded by a single load at the tip.

1.2 The cantilever beam

A cantilever beam is a flexural member which has one end build in to a wall or any other support and it can not move or rotate. This type of beam when acted upon a simple load at its end (in a transverse manner to its long axis) bends putting its top surface in tension and its bottom one in compression.

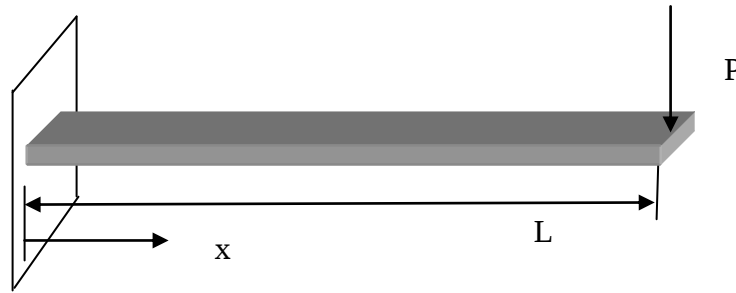


Figure 2. The cantilever beam specimen

Considering figure 2 it can be shown that the deflection curve of a cantilever is obtained or can be predicted by

$$y = \frac{P}{EI} \left(-\frac{Lx^2}{2} + \frac{x^3}{6} \right) \quad (2)$$

The slope of the deflection curve is given by

$$y' = \frac{P}{EI} \left(-Lx + \frac{x^2}{2} \right) \quad (3)$$

And the stress at the outer skin of the cantilever is given by

$$\sigma = \frac{tP}{2I} (-L + x) \quad (4)$$

P is the load, E is the Young's modulus of the material, I is the second moment of area of the beam given by $\frac{bt^3}{12}$ where b is the width, t is the thickness and x is the distance from the built in end of the beam, L is of course the total length of the beam. It is expected that a cantilever beam subjected to a single load at its free end, would deflect/bend away along the line of action of the load and experience a variable tensile stress on its top surface from zero value at the tip to maximum at the built in end. It follows that if there were compressive residual stresses present at the top surface of the beam they would oppose the tensile stresses generated by the applied load inhibiting/reducing the deflection, its slope and resulting surface stress on the beam. A comparison of the behaviour of a stress free beam to one which might contain "locked in" residual stresses would offer a strong probability of residual stress detection and quantification. The following section gives an account of the experiments that were performed in order to ascertain the suitability of Digital Shearography to detect and quantify residual stresses.

2.0 Experiments and results

Four mild steel specimens were machined to final dimensions of 250 mm long, 40 mm wide and 15.5 mm thick. In order to fully "stress relieve" the specimens after they had been prepared, they were annealed by first heating them from room temperature of approximately 25°C to maximum temperature of 625°C at 100 degrees intervals and subsequently cooling them from this maximum temperature to room temperature. Three specimens were subjected to different ways of inducing stresses on one surface. For specimen one, the stresses were induced by impacting the surface with the tips of the bristles of a wire brush while the second specimen was "shot peened" by covering the surface with 1.5 mm diameter steel "bearing" balls and impacting them with a hammer. For the third specimen, compressive stress was introduced on one of its surfaces by heating it to a dull orange colour and suddenly exposing the heated surface to cooling

water; that is, quenching it. The fourth specimen was left as annealed to act as the benchmark against the other three. The rectangular mild steel bars were mounted firmly by one end, at a length of 25 mm, vertically in a precision vice thus simulating a cantilever beam of 225 mm length. A force resulting from a mass of 1.425 kg was acted at the tip or the free end of the cantilever, via a rope and pulley, thus bending the beam toward the viewer (see figure 3). The opposite surface of the beam (the one with the residual stress) was placed in the optical field of the portable Digital Shearography system⁵. The shearograms obtained, as typified by those depicted in figure 4, served to obtain the plot of the distribution of the slope (gradients of the normal displacement) of the cantilever.

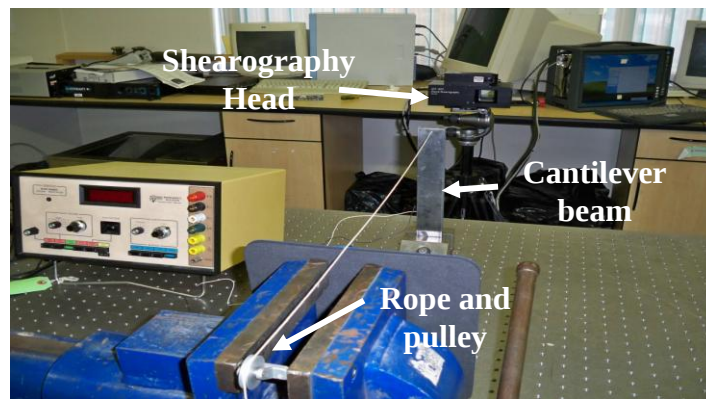


Figure 3. Experimental set-up of cantilever in bending

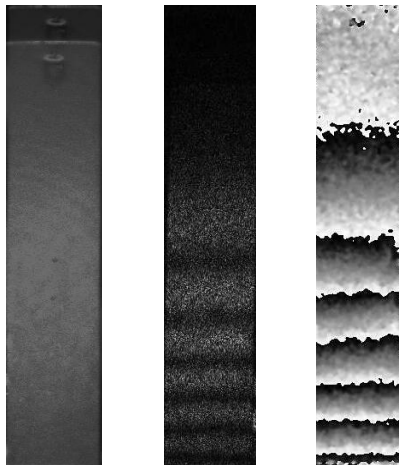


Figure 4. Typical images of the cantilever mounted vertically: On the left is the video image of the beam with the amount of shear visible, followed by an intensity shearogram and finally a phase stepped shearographic image.

By simply counting the number of the fringes and using equation 1 the slope of the cantilever (for the fourth specimen exemplified here) was determined for the respective fringe positions along the beam's length and plotted as depicted in figure 5. In the same figure the theoretical or predicted slope of the cantilever, obtained through equation 3, is also shown for comparison purposes. Excellent agreement is obtained between the predicted values and those obtained through the shearogram, provided the “correct” value of Young's modulus is used in equation 3. In this case a value of $E = 180$ GPa applied to equation 3 resulted in very good agreement between theory and experiment as seen in figure 5. This is an encouraging aspect of the results of this study in that it appears a relatively simple experiment may be used to yield quick and perhaps fairly accurate results for the value of E (Young's modulus) of materials.

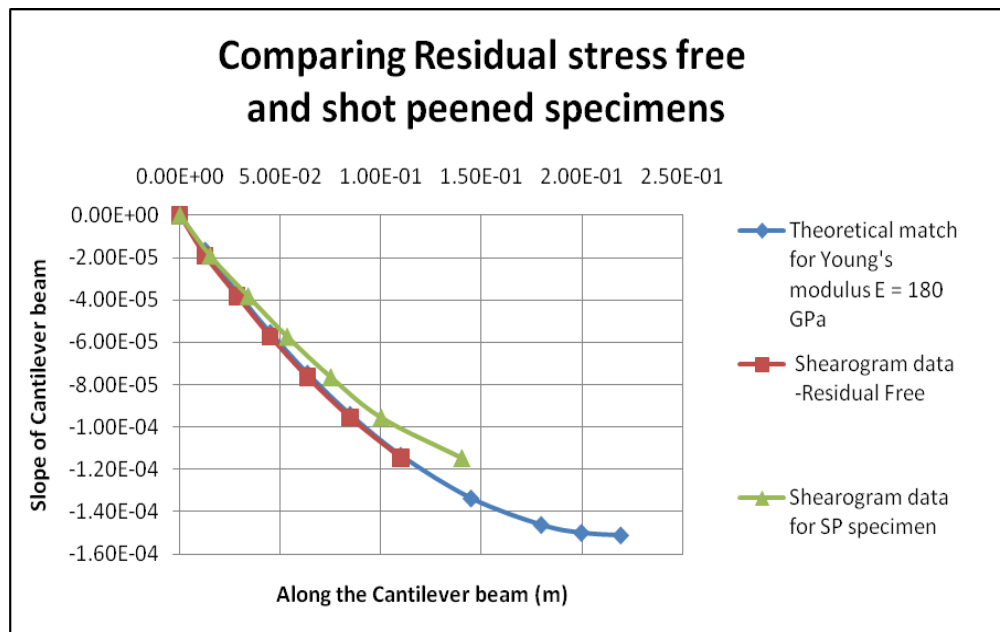


Figure 5. Theoretically predicted slope compared to the experimentally obtained ones for the “Residual stress free” and “shot peened” mild steel specimens

The data collected during the experiments are in the form of shearograms which enable the calculation of the slope of the cantilever beam's normal to the surface displacements at the points where a fringe is visible i.e. at a given distance from the built in end. In figure 5 a comparison is presented of the slope of the shot peened surface specimen to that of the residual stress free specimen and as expected the “s/p” specimen exhibits lesser slope values. A beam that contains compressive residual stresses at its top surface will resist the bending force and the resultant slope curve will be lesser in magnitude

when compared to the one from a beam that contains no residual stresses. In an analogous situation the lesser slope curve could be the result of a lesser bending force acting on a residual stress free beam. Therefore from the values of the experimentally determined slope curve (obtained using equation 1) we can extract this lesser in magnitude analogous or equivalent force (using equation 3) which will enable the calculation of the stress along the beam using equation 4. The difference of stress value between the one calculated based on the actual force (1.425 kg mass) and the one based on the equivalent force calculated as 1.244 kg mass, (both obtained using equation 4) would indicate the magnitude of the residual stresses existing in the beam and it should be constant along the length of the beam. What has been described above is illustrated in figure 6 depicting the stress distributions along the two beams and figure 7 which depicts the difference in stress between them. In figure 6 the maximum stress (at the built in end) approaches the value of 1.5MPa for the beam that had its surface shot peened (red line) and thus contained “locked in” or residual stresses of compressive nature. The blue line represents the tensile stress as predicted by theory reaching a maximum value of approximately 2.0MPa. The red line represents the stress as calculated from the analogous load yielded from the slope values experimentally recorded on the shearogram of the shot peened specimen. The pink line extrapolates to zero stress value, at the tip of the beam, as expected.

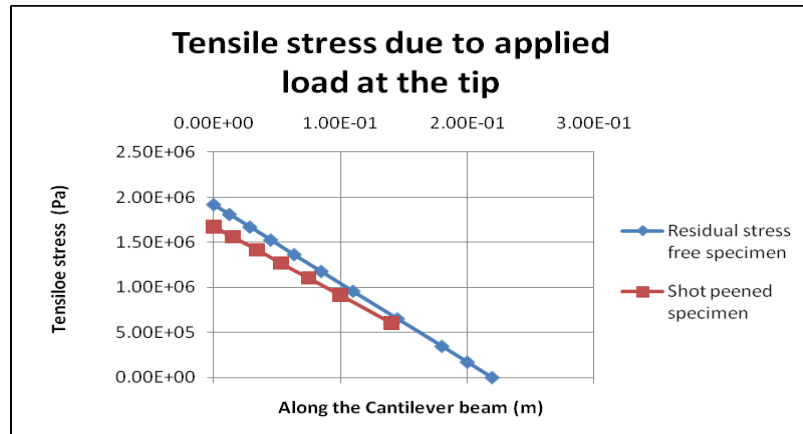


Figure 6. Resultant tensile stress on the top surface of the cantilevers due to the applied load at their tip of a mass of 1.425 kg

Finally figure 7 represents the result of the difference in tensile stress distribution between the residual stress free and the shot peened specimen. The results approximate a constant average value of approximately 250 kPa along the length of the beam however the last value as determined from the shearogram’s last fringe position (at a distance around $\frac{3}{4}$ of the length of the beam from the built in end) departs fairly radically from this average level.

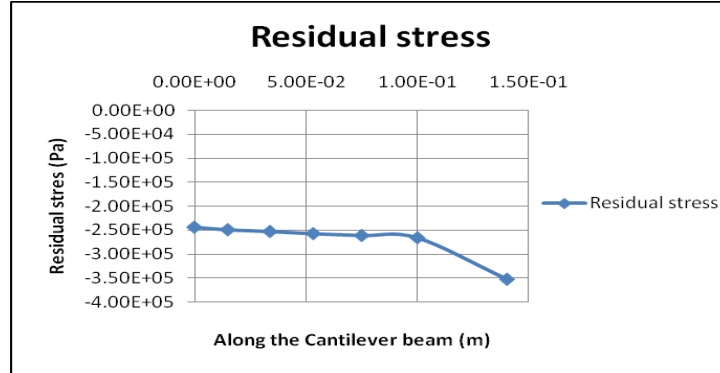


Figure 7. Experimentally determined residual stress in the shot peened specimen

3.0 Conclusions

It is felt that through this pilot/feasibility study the use of digital shearography, as a direct tool in determining residual stresses, merits further investigation. Certainly the advantages of digital shearography as a non-destructive, no contacting, full field, user friendly and capable of high sensitivity measurements, coupled with the results obtained here, hold promise toward the development of a novel technique in the field of residual stress determination. To that end further work encompassing independent measurements of existing residual stresses and the value of the Young's modulus of the material used for the beams are paramount. In addition the use of a cantilever beams subject to a load at the tip, of specimens made of all kinds of materials, could be refined as a user friendly and quick assessment method of the Young's modulus of the material.

References

1. C O Ruud "A review of selected non-destructive methods for residual stress measurement" NDT International pp 15-23 Feb. (1982)
2. P.J. Withers et al "Recent advances in residual stress measurement" International Journal of Pressure Vessels and Piping 85 118–127 (2008)
3. J Gryzgoridis and D Findeis "Benchmarking shearographic NDT for composites" Insight 50/ 5 pp 249-252 (2008)
4. J Gryzgoridis and D Findeis "Simultaneous Shearographic and Thermographic NDT of Aerospace Materials" Insight 48/5 pp 294-297 (2006)
5. <http://www.ndt.uct.ac.za> "prototypes"