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NEW APPROACHES TO ASSESSMENT OF STRESS AND STRAIN FIELDS WITH APPLICATION OF PHOTOSTRESS METHOD

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Abstract: *Isoclinic and isochromatic fringes provide qualitative and quantitative information in experimental method PhotoStress. They are the source of data on directions and magnitudes of principal strain and principal normal stress on the surface of analysed objects with photoelastic coating. The article reviews methodology of autonomous assessment of magnitudes and directions of stress fields and strains as carried out by the authors of the article by means of PhotoStress method.*

Keywords: ***Linear and circular polarization, isoclinics, isostatics, singular points, isochromatics.***

1. Introduction

Experimental method PhotoStress is based on temporary birefringence that appears in photoelastic coating applied to a tested object subjected to loads. When photoelastic coating applied to the tested object under load is illuminated with polarized light, two types of photoelastic entities can be observed: isoclinic and isochromatic fringes. These photoelastic entities allow us to perform qualitative (visual) and quantitative analysis of principal strain and principal normal stress directions and magnitudes on the surface of the object subjected to load. Quantitative analysis of principal strain and stress directions and magnitudes is performed manually at a point and hence is time-consuming when it comes to strain and stress determination at more points on the analysed surface. For the above-mentioned reasons, the authors of the article developed a PhotoStress software application that enables automatic determination of parameters of isoclinics and isochromatics from their images. From these parameters we can determine directions and magnitudes of principal strains and principal normal stresses at all points of tested surfaces.

2. Photoelastic entities

Isoclinic fringes are used in PhotoStress method in order to determine parameters of principal strains and principal normal stresses. They are dark lines or areas which are defined as geometrical points in which directions of principal stresses are parallel to intersected polarization planes of the polarizer and analyzer. Isoclinic fringes appear in a plane-polarized beam of light (Fig.1).

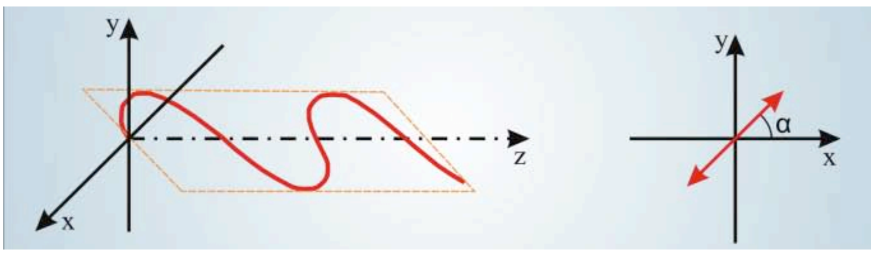

Fig. 1: Linear polarization.

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When examining isoclinic fringes, the axes of polarizer and analyzer are perpendicular to one another. When intersected polaroids rotate synchronically, the isoclinics viewed under reflection polariscope are continuously changing from the isoclinics with parameter 0° up to the isoclinics with parameter 90°. Isoclinics are distributed through the whole tested surface of an object under minimum load with respect to the changing directions of principal strains or stresses. Only one isoclinic with a particular parameter can intersect a particular point of a photoelastically coated test surface since in that point there is only one principal stress direction, i.e. α or $\alpha+\pi/2$.

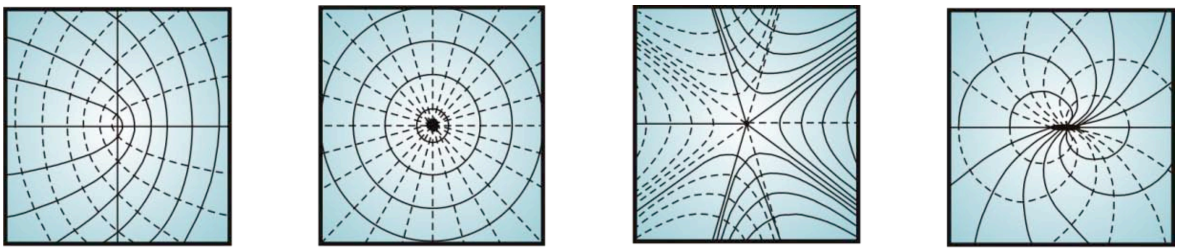
However, isoclinics of all parameters intersect points in which both principal stresses have the same magnitude and in which these stresses are principal in all directions. Such points are called singular points.

Singular points are points where both principal stresses are equal and hence

$$\sigma_1 = \sigma_2, \text{ or } \sigma_1 - \sigma_2 = 0.$$

Singular points have qualitative value for the behaviour analysis of isostatics and isochromatics. If $\sigma_1 = \sigma_2$, then the fringe order is expressed as $N = 0$. As a result, singular point is a zero-order isochromatic point. The material is at this point in the state of hydrostatic pressure ($\sigma_1 < 0$), tension ($\sigma_1 > 0$) or is in a stress-free state ($\sigma_1 = 0$) (Frocht, 1949).

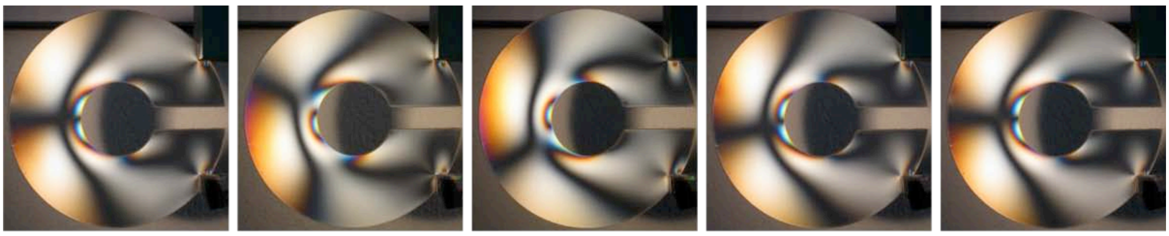
Singular points can be classified as the points of the first, second and higher orders. They can be further classified according to the behavior of isoclinics when the polariscope is being rotated (either positive or negative singular point). With respect to the nature of mathematical expressions for stress components, points of the second and higher order are not stable in the sense that even a slight change in the shape of the part, load or position causes a break-up into singular points of lower orders (for instance a point of the second order would break up into two points of the second order). Fig. 2 depicts a few examples of singular points of different orders that occur in the net system of isostatic curves.



a) b) c) d)

Fig. 2: Singular points of the a) first order, b) second order, c) third order, d) forth order.

The set of isostatic lines is displayed on the basis of the set of isoclinic fringes which were obtained at the angles from 0° to 90° with 5- or 10-degree increments and on the basis of classifications of singular points. Isostatic lines can be defined as stress trajectories. These are the sources of information about the directions of principal normal stresses σ_1 and σ_2 along the whole tested surface. Fig.3 depicts isoclinic fringes on an eccentrically loaded split ring obtained at 0°, 20°, 60°, 80° and 90° angle parameter. From the Fig.3 is evident that the isoclinics with 0° and 90° angle parameter are identical.



0° 20° 60° 80° 90°

Fig. 3: Isoclinic fringes on the eccentrically loaded split ring.

Traditional projections of a set of isoclinic fringes and isostatic lines are relatively time-consuming. The authors of the article hence developed a PhotoStress software application that enables a quick and simple projection of a set of isoclinic fringes and isostatic lines from the shot set of isoclinic lines taken at 0° up to 90° angle with 5- or 10-degree increments. In the application are isoclinic lines projected by means of quadratic Bézier curves which are determined by three control points. Fig.4 illustrates the projection of isoclinic lines in PhotoStress application.

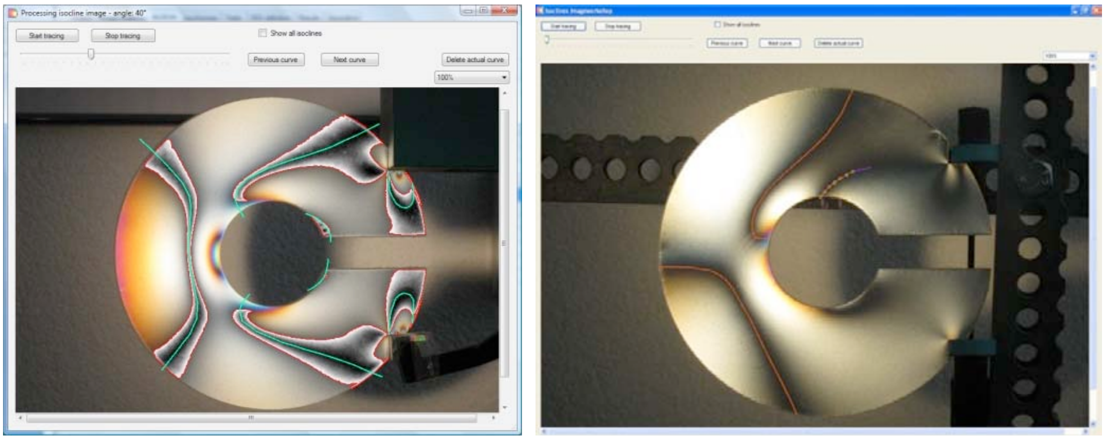
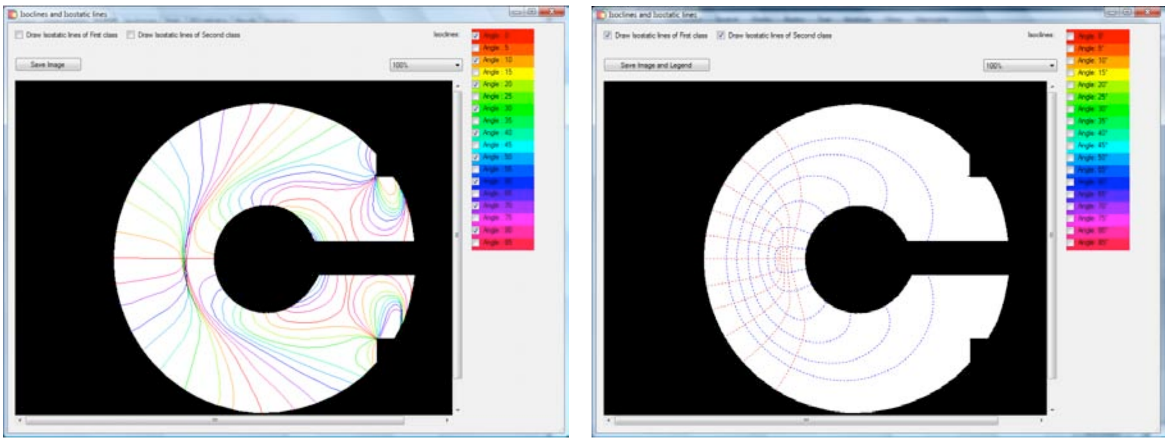


Fig. 4: Projection of isoclinics in PhotoStress application.

The approximation of principal strain or principal normal stress directions is performed in PhotoStress application on the basis of manually projected isoclinics with direction parameter α. The calculation of direction parameter for pixels, which are not included in the area of defined lines, is done on the basis of weighted average of direction parameter of the two closest pixels which belong to drawn isolcinics with a different direction parameter. Important is in this case the distance between the pixel being calculated and the pixel that belongs to some isoclinics.

Fig.5a depicts the set of isoclinics of a split ring subjected to diametrical pressure with the angle increment 5° as being projected in PhotoStress application. The set of isoclinic fringes of the first and second type is shown in the fig.5b. Blue curves represent isostatic lines of the first type and red curves represent isostatic lines of the second type.



a) **b)**

Fig. 5: a) the set of isoclinic fringes, b) projection of the set of isostatic lines.

The above-mentioned isoclinic and isostatic curves are the source of information about the behaviour of principal strains or principal normal stresses. Quantitative information about strain and stress magnitudes at particular points of the photoelastically coated surface of a tested object can be derived from another type of photoelastic lines, i.e. isochromatic fringes. Isochromatics are connection lines of points along which the difference between principal normal stresses $\sigma_1 - \sigma_2$ is constant. They occur in a circle-polarized light (Fig.6). Deformations of some photoelastically coated object under load are transformed to the photoelastic coating. When illuminated with polarized light from reflection polariscope, surface deformations appear as colourful isochromatic fringes or the areas of the same (iso) colour (chromos).

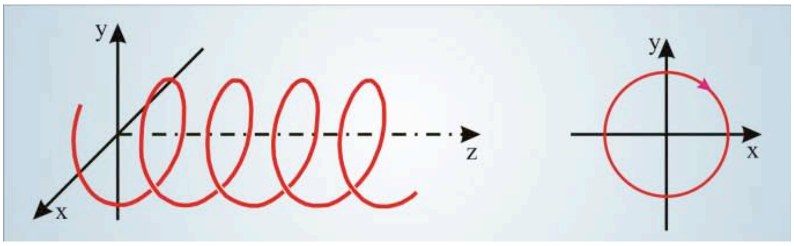


Fig. 6: Circular polarization.

When the load is applied to the tested object in increments, isochromatic fringes will appear first at the most highly stressed points. As the load is increased and new fringes appear, the earlier fringes are pushed toward areas of lower stresses. The appearance of isochromatic fringes is dependent upon optical sensitivity of applied photoelastic coating and load applied to the object. A specific number of isochromatic fringes can appear on the photoelastic coating. These are numbered as n-order isochromatics. The colour of each fringe represents specific birefringence or fringe order *N*. Full colour order, relative lags and numerical fringe order for each colour can be found in Trebuňa (2006).
In the full-field strain and stress analysis of isochromatic fringes it is required to know the relationship between colourful isochromatic fringes obtained through PhotoStress method and strain or stress.

The basic relation for PhotoStress method is expressed as follows:

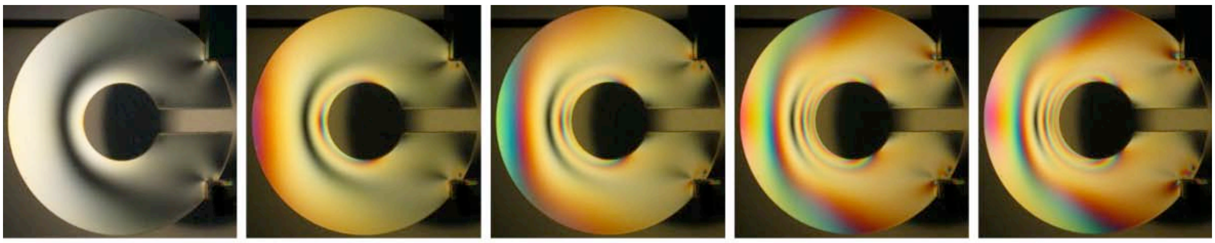
relative elongation (ε) = calibration constant (f) x fringe order value (N)

where f is fringe value of photoelastic coating,

N - fringe order value read from the compensator during manual determination of photoelastic fringe order at particular point.

There is a linear relationship between the fringe order value N and strain ε, i.e. with the increase of fringe order value N at given fringe value f strain or stress value increases as well.

Fig.7 illustrates isochromatic fringes that occur when the split ring is subjected to incremental loading by diametrical pressure.



Loading 1 Loading 2 Loading 3 Loading 4 Loading 5

Fig. 7: Isochromatic fringes during incremental loading of a split ring by diametrical pressure.

Null-Balance Compensator (Fig.8) is used in PhotoStress method for manual determination of fringe order value at analysed point. The compensator can determine fringe order value only at one point. However, this process is time-consuming in the analysis at more points of tested surface.

Fig. 8: Null-Balance Compensator model 832.

Nevertheless, with PhotoStress application full-field automatic analysis of colourful isochromatic fringes can be done. It allows us to determine principal strains and principal normal stresses not only at a point, but also along line and surface.

In PhotoStress application, the area of colourful isochromatic fringes is divided into two sub-areas (Fig.9):

- area with the order of isochromatic fringes N from 0 to $0{,}35$,
- area with the order of isochromatic fringes N from $0{,}36$ to $3{,}00$.

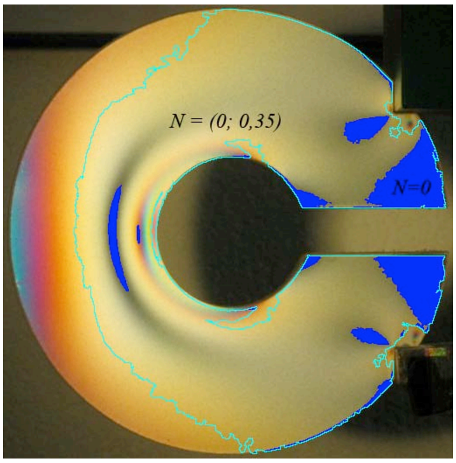


Fig. 9: The area of colourful isochromatic fringes.

In the areas with the values of fringe orders lower than $0{,}35$, colours are faint and gradient method is applied in order to calculate isochromatic fringe order. At the beginning, the darkest area (the area of zero point) should be marked. Then, on the surface that arose when blue and green luminance components merged together, the shortest trajectories between zero point area and isochromatic fringe with 0,35 fringe order should be found by means of gradient method. Each point in that area will be assigned fringe order value with respect to the relation of its distance from the zero point and the isochromatic fringe with fringe order 0,35 within given trajectory.

For determination of isochromatic fringe order in the area with N from $0{,}36$ to $3{,}00$ is the algorithm of PhotoStress application based on determination of colour of a given pixel in HSV colour space and its index, which represents the order in which six photoelastic colours re-occur from the order $N = 0$. Each pixel from the picture of a colourful photoelastic pattern surrounded by logical mask is assigned specific value of RGB colour. The value of RGB colour specifies relative intensity of red, green and blue. However, this does not suffice in PhotoStress method. For this reason, HSV colour space is more useful when using PhotoStress method. PhotoStress application thus includes algorithm for transformation of colour components from RGB colour space into HSV colour space.

Fig.10 shows determination of zero points and colourful isochromatic fringes of tested split ring by PhotoStress application.

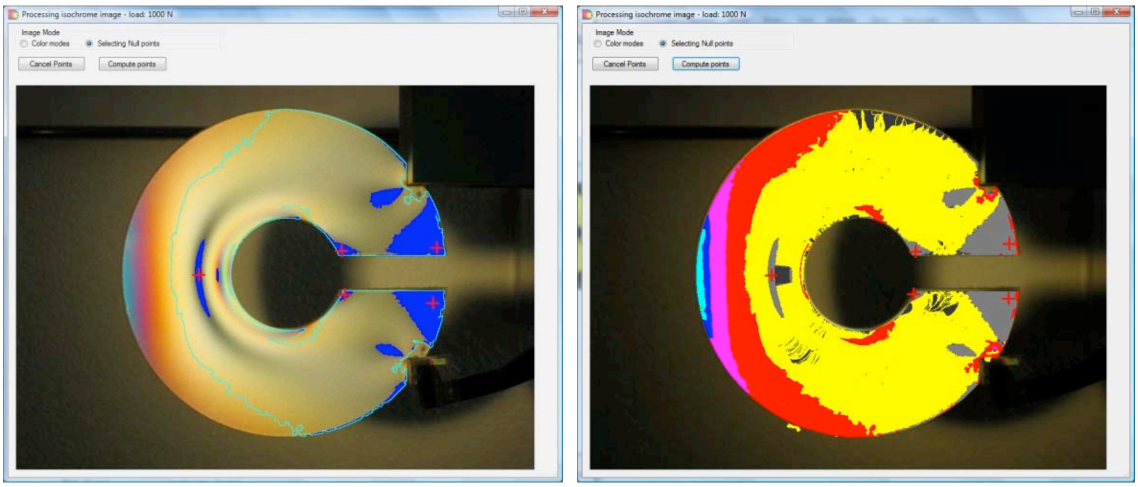


Fig. 10: Conversion of colourful isochromatic fringes to the fringe order N.

3. Conclusions

As it is evident from the article, software application PhotoStress makes the analysis of principal strain and principal normal stress directions and magnitudes on photoelastically coated objects faster. The foundations of this improvement lie in automatic processing of photoelastic entities such as isoclinic fringes, singular points and isochromatic fringes. The application is currently subjected to some improvements regarding little imperfections that arise during automatic projection of isostatic curves and recognition of colourful isochromatic fringes or surfaces. Amendments and other additions to the software application will be discussed in future articles.

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