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Automatization of strain and stress fields assessment based on the principles of reflection photoelasticity

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Abstract:

Typical reflection photoelasticity enables to determine directions and magnitudes of principal strains and principal normal stresses in a particular point. This is usually a long-lasting process if we focus on such determination in more points. Image digitalization and development of new hardware go hand in hand with automatization of usual experimental methods such as reflection photoelasticity. In the department of the authors of this paper and in relation to these possibilities, the application PhotoStress has been developed for full-field analysis of strains and stresses in photoelastically coated objects. This paper demonstrates strain and stress analysis while using the application PhotoStress and presents other intensively discussed possibilities for improvement of the current version.

Keywords: reflection photoelasticity, PSCalc™ software, PhotoStress software,

1. Introduction

Reflection photoelasticity is an optical experimental method which can be applied for a complex full-field stress and strain analysis of photoelastically coated structure parts. This method allows us not only to observe the distribution of strains and stresses that appear as colourful isochromatic fringes, but also, in a quantitative way, to determine the values of direction and magnitude of principal strains and principal normal stresses in any surface point of a photoelastically coated test object. There are two kinds of photoelastic fringes which can be used for quantitative determination of principal strains and principal normal stresses – isoclinic and isochromatic fringes. Isoclinic fringes are the source of information on directions and isochromatic fringes provide us with information on magnitudes of principal strains and principal stresses in any point of a chosen phoelastically coated object. For quantitative determination of directions and magnitudes of principal stresses we use optical devices, i.e. reflection polariscopes. In our workplace, there are currently three reflection polariscopes available (M030, M040, LF/Z-2) with LF/Z-2 (Fig. 1) being the latest one.

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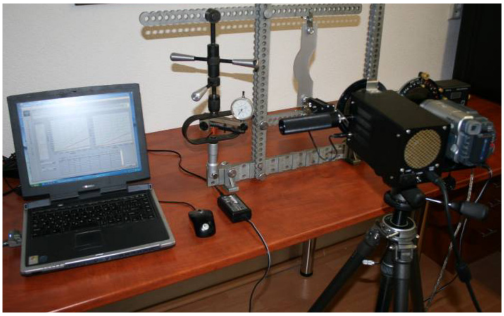

Fig. 1. Reflection polariscope LF/Z-2.

LF/Z-2 polariscope consists of light source, polariser, analyser, laser illumination, compensator and digital camera which transmits photoelastic image to the software PSCalc^{TM}.

2. Basic principle of reflection photoelasticity

Reflection photoelasticity is based on relation between colourful isochromatic image, strain and stress. The basic relation of reflection photoelasticity can be expressed as follows:

$$\textit{strain } (\varepsilon) = \textit{calibration constant } (f) \textit{ x fringe order value } (N)$$

- f calibration constant (fringe constant) of the material used for photoelastic coating
- N fringe order value in a measured point

If fringe order value N rises at given calibration constant f, strain ε rises as well. This can be observed on photoelastically coated aluminium console (Fig. 2). The colour (order) of isochromatic fringes changes in the direction of an increasing stress from the black colour ($N=0$) to the green colour ($N=3, 2$). The complete list of colours and their relevant fringe order values can be found in [12, 15].

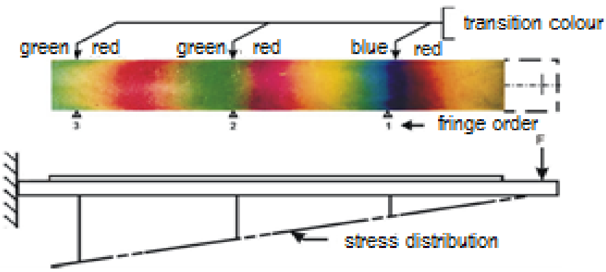

Fig. 2. Distribution of coloured isochromatic fringes on photoelastically coated aluminium console.

Basic relations for strain and stress analysis as applied in the method of reflection photoelasticity can be expressed as follows:

$$\varepsilon_1 - \varepsilon_2 = (N - N_0) \cdot f, \tag{1}$$

$$\sigma_1 - \sigma_2 = \frac{E}{1+\mu}(N - N_0) \cdot f, \tag{2}$$

where ε_1, ε_2, are principal strains, σ_1, σ, are principal normal stresses, f is the fringe constant of the material used for photoelastic coating, E is Young's Modulus of elasticity in tested object, μ is Poisson's ratio in the material of tested object, N_0 is the initial value on compensator, and N is the final value on compensator.

3. PSCalc™ software

As a part of the reflection polariscope LF/Z-2, the software PSCalc™ (Fig.3) is used to determine the difference and values of particular (separate) principal strains and principal normal stresses in given points of photoelastically coated surface of a loaded test object.

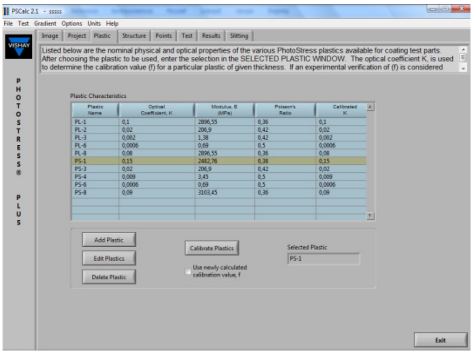

Fig. 3. Software environment in PSCalc™ software.

For determination of individual (separate) values of principal strains and principal normal stresses out of free boundaries of a tested object the software uses the Slitting Method.

There are three equations for the Slitting Method in the programme which are applicable for a notch in direction ε_1, σ_1. The equations are dependent upon whether the compensator axis is parallel to the edge of the notch or perpendicular to it.

When measuring in the direction of the notch with the compensator axis parallel to the edge of the notch, the relation is expressed as follows:

$$\varepsilon_1 = \frac{f}{1+\mu_c} \cdot (N - N_0). \tag{3}$$

When measuring in the direction of the notch edge with the compensator axis being perpendicular to the edge of the notch, the relation is expressed as follows:

$$\varepsilon_1 = -\frac{f}{1+\mu_c} \cdot \left(N - N_0\right). \qquad (4)$$

From the relation (1) we can derive the relation for strain in the direction 2

$$\varepsilon_2 = \varepsilon_2 - f \cdot \left(N - N_0\right) \qquad (5)$$

The only difference between equations (3) and (4) is that in the sign.

The output of the software are numerical values and distribution of differences and principal strains (ε_1-ε_2, ε_1, ε_2) and principal normal stresses (σ_1- σ_2, σ_1, σ_2) (Fig.4) [9, 10, 11].

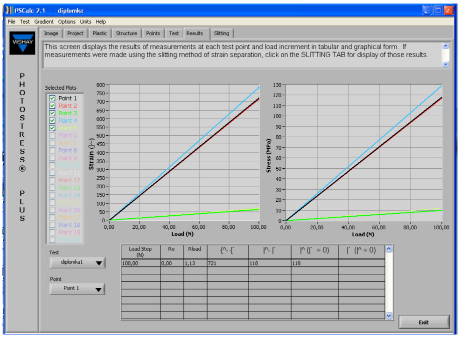

Fig. 4. Distribution of principal strains and principal normal stress displayed as a graphical output of PSCalc™ software.

4. PhotoStress software

Seeking to make full-field analysis of strain and stress fields faster, as carried out by reflection photoelasticity method, the department of the authors of this article have developed a software application which processes digital images of isoclinic and coloured isochromatic fringes so that directions and magnitudes of principal strains and principal normal stresses can be determined. PhotoStress software is based on the principle of colour recognition in particular pixels in digital picture of coloured isochromatic fringes which occur during loading and can be seen when a photoelastically coated surface of a tested object is illuminated by polarised light.

In the zero-point area (N=0) it is difficult to determine the colour of particular pixels from digital picture of coloured isochromatic fringes and simultaneously determine the fringe order value N. For the above-mentioned reason, the area needs to be divided into two subareas (Fig. 5).

- the subarea where the order of isochromatic fringes N ranges between *0* and *0,35*,
- the subarea where the order of isochromatic fringes N ranges between *0,36* and *3,00*.

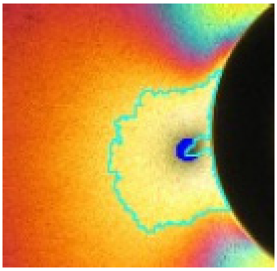

Fig. 5. Division of the area of isochromatic fringes.

In the subarea with the fringe order values *N* lower than *0,35* are the colours pale. Hence, the fringe order is calculated by means of a gradient method. At the beginning of the process, the darkest area (the zero-point area) is determined by thresholding from blue-colour component. Subsequently, in the field that arises from the merging of blue and green luminance components the shortest trajectories between the zero-point area and the isochromatic fringe with the fringe order value *N=0,35* are to be found by means of a gradient method. Each point is then assigned specific fringe order value according to the relation of its distance from the zero-point area and the isochromatic fringe with the fringe order *N=0,*35 within given trajectory.

Algorithm for determination of isochromatic fringe order in the subarea where fringe order values *N* range between *0,36* and *3,00* is based on the 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 then assigned specific value of RGB colour. The value of RGB colour specifies relative intensity of red, green and blue colour. However, this does not suffice in the method of reflection photoelasticity. For this reason, HSV colour space is more useful. The software application thus includes algorithm for transformation of colour components from RGB colour space (Fig. 6) into HSV colour space (Fig.7).

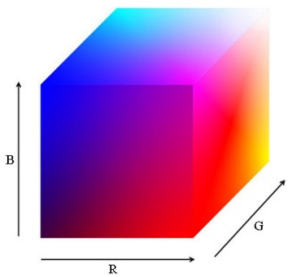

Fig. 6. RGB colour space.

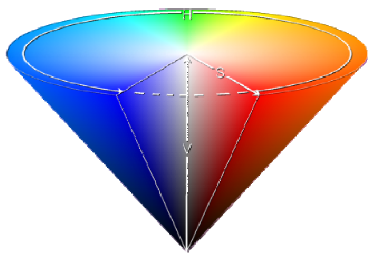

Fig. 7. HSV colour space.

The software works with HSV colour model for calculations of isochromatic fringe orders, where the value *H* represents the colour shade of a given pixel. When indexing particular pixels in the tested area determined by a mask, FloodFill algorithm with eight directions is applied. This algorithm assigns each value H specific value of the fringe order N in that particular point, or in that particular pixel of digital picture. From the colour of the pixel and from its index it is possible to determine the fringe order value on the basis of transformation function. This transformation function is set on the basis of calibration measurements that were carried out by means of reflection polariscope LF/Z-2 on a beam with photoelastic coating PS-1 under four-point bending (Fig. 8).

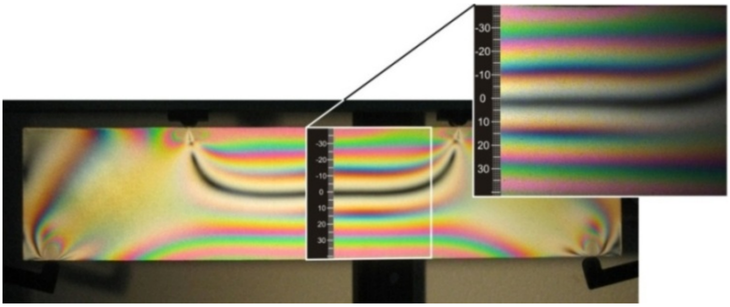

Fig. 8. Calibration sample – the beam under four-point bending.

The calibration process has its principle in manual reading of isochromatic fringe orders in precisely determined points on the calibration beam by means of reflection polariscope LF/Z-2 and a compensator (Model 832). Measurement points were determined by PhotoStress application and are depicted as line sections in transition areas of isochromatic fringes (Fig.9, Fig.10).

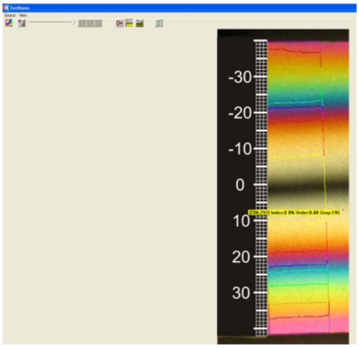

Fig. 9. Calibration sample – loading 1.

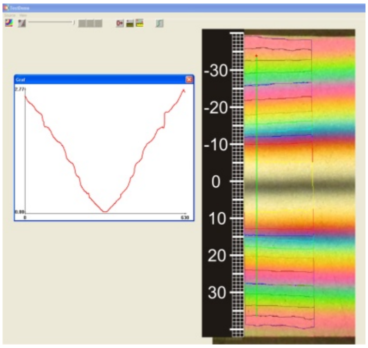

Fig. 10. Calibration sample – loading 1.

From the results of calibration measurements we were able to make Calibration table 1 which includes measurement points determined by PhotoStress application, colour index, fringe order values in these points read by means of a compensator (Model 832), arithmetic mean of the read fringe order values in two different points while having the same colour index, component H of the colour space HSV in standard units SU ranging *<0;255>* and degrees ranging *<0°;360°>*.

Table 1. Calibration table

Figure	Colour index	Hue [SU] <0;255>	Hue [°] <0;360>	Measurement point [mm]	Fringe order [-]	Measurement points [mm]	Fringe order [-]	Fringe order (arithmetic mean) [-]
	1	42	59,29412	11,0	0,33	-7,5	0,39	0,36
	2	85	120	19,0	0,77	-17,0	0,76	0,765
	3	128	180,7059	22,0	0,88	-20,0	0,98	0,93
Fig. 9	4	170	240	23,0	0,99	-21,0	1,03	1,01
	5	213	300,7059	24,5	1,11	-22,5	1,09	1,1
	6	0	0	28,0	1,22	-26,5	1,24	1,23
	7	42	59,29412	33,0	1,55	-32,5	1,55	1,55
	8	85	120	37,0	1,77	-37,5	1,71	1,74
	8	85	120	24,0	1,77	-22,0	1,74	1,755
	9	128	180,7059	27,5	2,06	-25,5	1,99	2,025
	11	170	240	28,0	2,09	-26,0	2,03	2,06
Fig.10	12	213	300,7059	30,5	2,32	-29,0	2,25	2,285
	13	0	0	33,0	2,50	-32,5	2,48	2,49
	14	42	59,29412	36,0	2,77	-36,0	2,66	2,715
	15	85	120	38,5	2,98	-40,0	2,94	2,96

The dependence of the arithmetic mean of the fringe order in relation to the colour index in measurement point is shown in Fig. 11. On the basis of this dependence, values of principal strains and principal normal stresses can be calculated in the whole tested surface of given photoelastically coated object [6, 7].

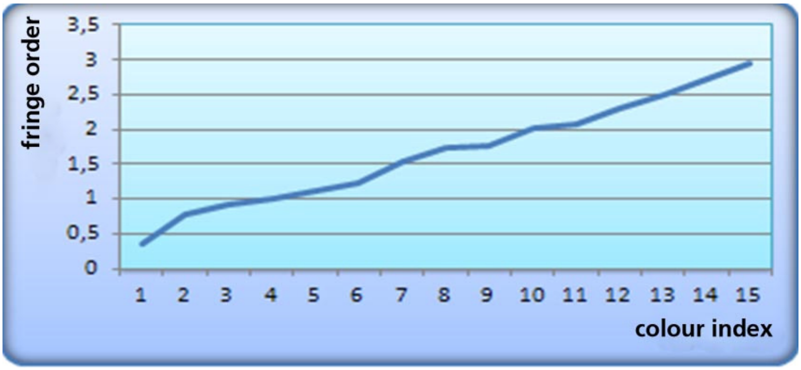

Fig. 11. Behaviour of isochromatic fringe order in dependence on colour index.

As an output of the software we get numerical values in form of the table and direction together with magnitudes of principal strains and principal normal stresses in a point, line or throughout the surface. As an example, the Fig. 12 depicts the behaviour of direction parameters. The behaviour was determined by PhotoStress software while measuring angle parameters of the sample in line.

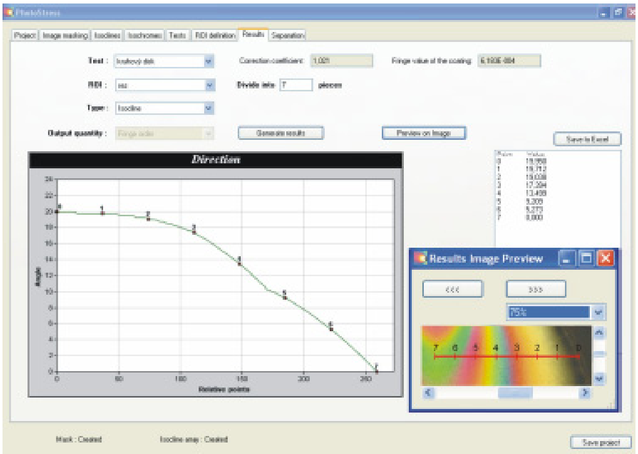

Fig. 12. Behaviour of zero parameters of the direction of principal normal stresses.

5. Conclusion

PSCalc™ software allows us to measure principal strains and principal stresses in a given point when reflection polariscope LF/Z-2 is used. The measurement can be done only from one point to another and, hence, is a long-lasting process when measurements in more points are required. Determination of separate values relies only on Slitting.

PhotoStress software offers us the possibility to measure with reflection polariscopes M030, M040 and LF/Z-2 and includes tree separation methods: shear stress difference method, strain gage separator method and Slitting method. The analysis of parameters and the assessment of required values is a quick process and it simultaneously enables measurements in a point, line and throughout the surface.

There are details in the PhotoStress programme being improved at the moment, regarding colour recognition in particular pixels, and is being amended by the following options: online image transmission by HD camera, calibration for various photoelastic materials etc. All the improvements and amendments of the PhotoStress software will be included in forthcoming articles.

Acknowledgements

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References

[1] Frocht, M.M.: Photoelasticity I., New York: *John Wiley*, 1949, 411 s.

[2] Frocht, M.M.: Photoelasticity II., New York: *John Wiley*, 1957, 505 s.

[3] Kobayashi, A.S.: Handbook on Experimental Mechanics. Seattle: *Society for Experimental Mechanics*, 1993, 1020 s. ISBN1-56081-640-6.

[4] Macura, P., Experimental Stress Analysis of Transducers by Means of PhotoStress Method. In: *Acta Mechanica Slovaca*. Roč. 14, č. 4 (2010), s. 52-57. ISSN 1335-2393

[5] Milbauer, M., Perla, M.: Fotoelasticimetrické přístroje a měřicí metody. *ČSAV*, Praha, 1959, 471 s.

[6] Ostertagová, E.: Aplikovaná štatistika. *Elfa*, Košice, 2011. 161 s. ISBN 978-80-8086-171-1.

[7] Ostertag, O., Ostertagová, E.: Automatizácia merania a vyhodnotenia napätosti programovým systémom photoelast. In: Bulletin of Applied Mechanics. Vol. 2, no. 6 2006, p. 105-119., ISSN 1801-1217.

[8] Ramesh, K.: Digital Photoelasticity - Advanced Techniques and Applications, *Springer-Verlag*, Berlin, Germany, 2000, ISBN: 3-540-66795-4.

[9] Tech Note TN-702-2 Introduction to Stress Analysis by the PhotoStress Method, 2011

[10] Tech Note TN-706-1 Corrections to Photoelastic coatings fringe-order, 2011

[11] Tech Note TN-708-2 Principal Stress Separation in PhotoStress® Measurements, 2011

[12] Trebuňa, F.: Princípy, postupy, prístroje v metóde PhotoStress. *TypoPress*, Košice, 2006, 360 s., ISBN 80-8073-670-7.

[13] Trebuňa, F., Frankovský, P., Huňady R.: Optical methods and their application in experimental analysis of mechanical and mechatronic systems. In: *Hutnické listy*. Vol. 64, no. 7 (2011), pp. 173-178., ISSN 0018-8069.

[14] Trebuňa, F. et al.: Abilities of New Software for PhotoStress Method. In: *EAN 2010*, Proceeding - 48th International Scientific Conference, Olomouc: Palacky University Olomouc, 2010, ISBN 978-80-244-2533-7.

[15] Trebuňa, F., Šimčák, F.: Príručka experimentálnej mechaniky. *TypoPress*, Košice, 2007, 1526 s. ISBN 970-80-8073-816-7.