Acta Mechanica Slovaca 14 (4): 82-91, 2010
DOI: 10.2478/v10147-011-0038-4

Further Possibilities of Using Software PhotoStress for Separation of Principal Normal Stresses

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KEY WORDS

Software PhotoStress, Separation Methods, Reflection Polariscope M030, Reflection Polariscope M040

ABSTRACT

Software PhotoStress, elaborated in our laboratories allows determination of directions and magnitudes of strains or principal normal stresses in loaded photoelastically coated structural elements. It allows accelerating process of measurement and evaluation of deformations or stresses in point, along line or along curve, respectively. In those enti-

ties can be determined directions, and magnitudes of differences and separated principal deformations or stresses on the basis of photography of loaded photoelastically coated objects. In the paper is given procedure for of evaluation of separated principal normal stresses by using of separation methods: method of difference of shear stresses with using separation strain gage and method of oblique incidence.

INTRODUCTION

The workplace of authors is equipped with measurement devices determined for measurement of direction parameters and differences of principal strains or stresses by PhotoStress method. The polariscopes M030, M040 and LF/Z-2 allows determination of parameters of direction and differences of principal stresses and consequently on the base of experimentally determined further parameter to separate principal stresses or principal strains. It is relatively lengthy process especially if it is applied in several points of coated surface. In order to accelerate this process was created new software application *PhotoStress* that simply on the base of photography of color isochromatic fringes of loaded objects allows to determine directions and separate magnitudes of principal strains or normal stresses in point, line or curve. For determination of further parameter that is necessary for separation of values of principal stresses are in the application built in separation methods - Slitting method, method of oblique incidence, method of separation strain gage and method of shear stress differences. The base principle of application *PhotoStress* with example of determination of direction and magnitude of principal normal stresses in partite ring by using Slitting method of separation was published in paper [4].

In the paper is given procedure for measurement of principal normal stresses by program PhotoStress using reflection polariscopes M030, M040 and LF/Z-2. For separation of individual principal normal stresses in analyzed entities of fork spanner and beam with notches are used separation methods - method of shear stress differences, method of oblique incidence and separation method with using separation strain gage.

Application *PhotoStress* (Fig. 1) is based on recognizing of colors of individual pixels of color isochromatic fringes that are created during loading and lightening of coated objects with polarized light by reflection polariscope. From the color of individual pixels of a photograph it determines order of isochromatic fringes needed for determination of differences of principal strains and principal normal stresses. On the basis of photographs of isocline lines the application allows to determine direction of principal strains or principal normal stresses in individual pixels of analyzed surface. Output of the program is directions and magnitudes of principal strains or principal normal stresses in the form of a table or in graphical form [5].

Fig. 1 *Application PhotoStress*

The process of measurement begins with creation of new project with import of photographs of isoclines and isochromatic fringes of loaded photoelastically coated part in format jpg into application PhotoStress.

For determination of directions and drawing of isoatatic lines of the I-st and II-nd kind for the whole analyzed surface is necessary to import photographs of isocline lines with maximal increment 10° in the range from 0° to 90°. Further step is determination of principal strains or stresses. In this step is necessary to import photograph of color isochromatic fringes of analyzed loaded specimen. Further step is development of so-called mask that serve for separating of analyzed part of object from background (Fig. 2). Creation of mask relates on drawing contours of investigated part. In pictures are then evaluated only pixels that are contained in created mask [2].

Analyzed field of isochromatic fringes is in application PhotoStress splitted into two areas (Fig. 3):

- *area of isochromatic fringe orders N in range from 0 to 0,35 (area 1),*
- *area of isochromatic fringe orders N in range from 0,36 to 3,00 (area 2).*

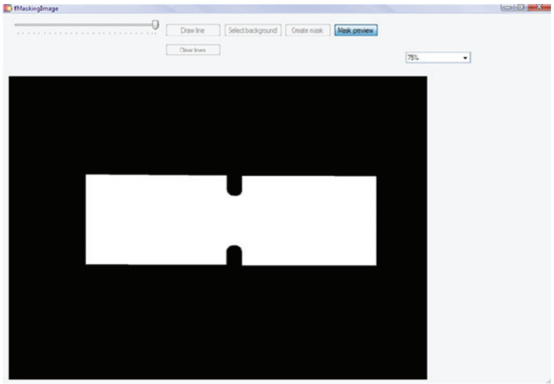

Fig. 2 *Creation of mask*

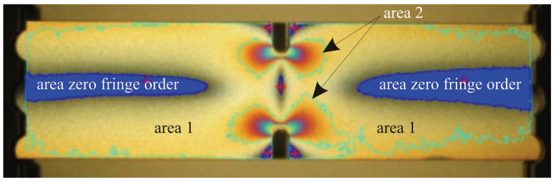

Fig. 3 *Splitting of area of isochromatic fringes*

In areas where the isochromatic fringe orders are smaller than *0,36* are the colors very inconspicuous. Fringe order for every pixel in that area is determined by gradient method. Gradient method is based on searching of shortest trajectory between area of null point and isochromat with fringe order *0,36*. To the every point in this area is given fringe order on the base of ratio of its distance from null point to isochrom line of order 0.36 in the frame of given trajectory. Algorithm for determination of isochromatic fringe order in area of fringe orders in range from 0.36 to 3.00 is based on determination of color of given pixel (in HSV color space, where Hue determines prevailing spectral color, *Saturation* determines to how extent is the color clear and Value describes the measure of brightness) and its index that represents order of repeating of six color fotoelastic colors. To the every point of color fotoelastic pattern is given RGB value of color space. This value represents relative intensity of red, green, and blue color, which is not enough for PhotoStress® method. That is a reason why is in PhotoStress built algorithm for transformation of color components from RGB color space to HSV color space. During the recomputation of individual color pixels to value of fringe order is used value H (Hue). To this value is given value of fringe order *N* according to defined transformation function. To the sequential indexing of analyzed area is used 8-directional algorithm FloodFill.

SEPARATION OF PRINCIPAL NORMAL STRESSES WITH USING METHOD OF DIFFERENCES OF SHEAR STRESSES AND METHOD OF SEPARATION STRAIN GAGE

Determination of individual principal normal stresses by program PhotoStress with using reflective polariscope M040 was accomplished on the fork spanner according to Fig. 4. For separation of individual principal normal stresses in analyzed points was used method of shear stresses while the starting point of separation does not lie on unloaded boundary of coated spanner, but in area of plane stress. In that point was realized, at first, separation of principal strains ε_1 and ε_2 by separation strain gage photostress. Consequently were from those strains determined principal normal stresses σ_1, σ_2 and normal stresses σ_x, σ_y in beginning point of path of separation by method of differences of shear stresses. In the next analyzed points was the separation of principal normal stresses realized by method of differences of shear stresses.

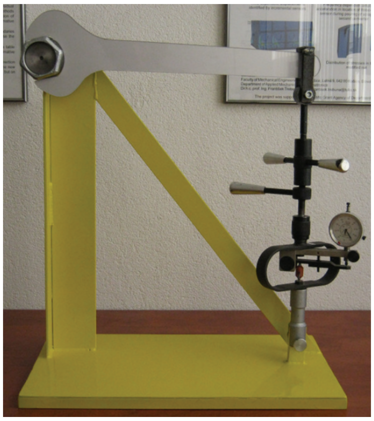

Fig. 4 *Loading of fork spanner*

Fork spanner was made from steel sheet STN 11 523 of thickness 5 mm by laser and then coated by photoelastic coating PS-1 of thickness 3,125 mm (Fig. 5) by glue PC-1. Mechanical properties of steel sheet and photoelastic coating are given in Tab. 1.

Fig. 5 *Fork spanner made from steel sheet and photoelastic coating*

Steel sheet STN 11 523		**Photoelastic coating PS-1**			
E [MPa]	μ [-]	E [MPa]	μ [-]	K [-]	f [με/fringe]
2,1.10[5]	0,3	2,1.10[5]	0,3	0,15	583

Tav. 1 *Mechanical properties of steel sheet and photoelastic coating.*

The pictures of isoclines (Fig. 6) in range *0°* to *90°* with increment *10°*, for which were determined principal normal stresses in analyzed points in line regions were made by digital camera and reflection polariscope M040.
In Fig. 7 is given distribution of color isochromatic fringes for successive loading of fork spanner from 400N to 1600N and investigated by reflection polariscope M040. Separation of principal strains ε_1, ε_2 and separation of normal stresses σ_x, σ_y on fork spanner was accomplished for loading force F=1600N.
As is seen from Fig. 7, the isochromatic fringes after loading are at first in locations of highest stress that is in locations of contact of spanner with a bolt. For successive increasing of loading are the fringes shifted to the areas with lower stress. Black areas, areas of null fringe order (singular points) are characterized by zero difference of principal strains or stresses and they are starting areas for analysis of color isochromatic fringes in program PhotoStress.
Principal normal stresses in points 0 to 10 of line region (Fig. 8) were determined with using reflection polariscope M040 and digital camera CANON A380 during loading by force *F=1600 N*.
Points 0 to 10, in which was accomplished separation are given in Fig. 9. Point 0 is starting point for separation of principal normal stresses by the method of shear stress differences. For separation of principal normal stresses by the method of shear stress differences is necessary to give magnitude of stress σ_x in *starting point* of separation path. Point 0 lies in the inner area of coated spanner in which is plane stress state. In that point is necessary to determine magnitudes of individual normal stresses σ_x and

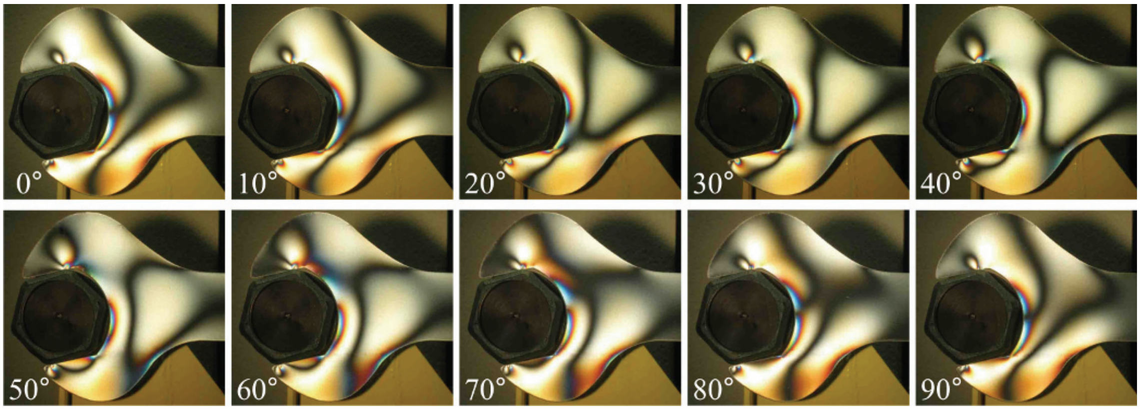

Fig. 6 *Isocline lines on fork spanner*

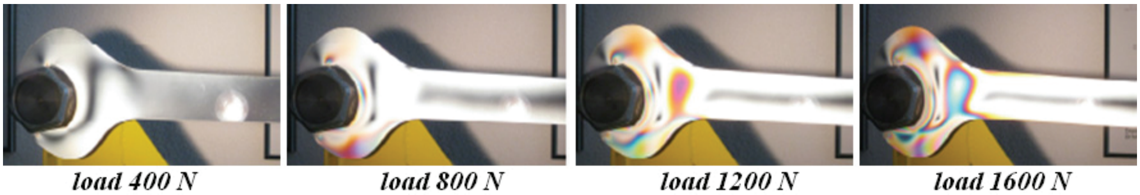

Fig. 7 *Sequential loading of fork spanner investigated by polariscope M 040*

σ_y. For determination of such stresses in a point 0 was accomplished second measurement by special electrical resistance strain gage PhotoStress Separator Gage.

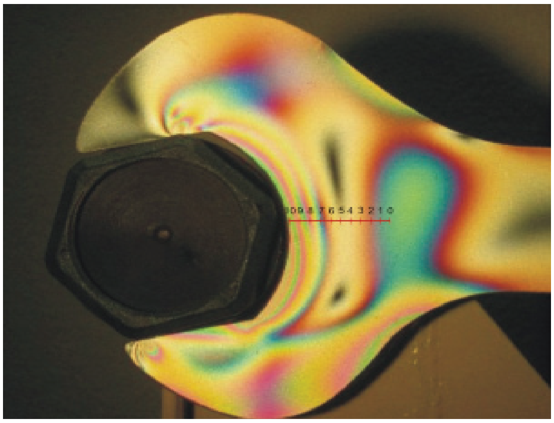

Fig. 8 *Sequential loading of fork spanner investigated by polariscope M 040*

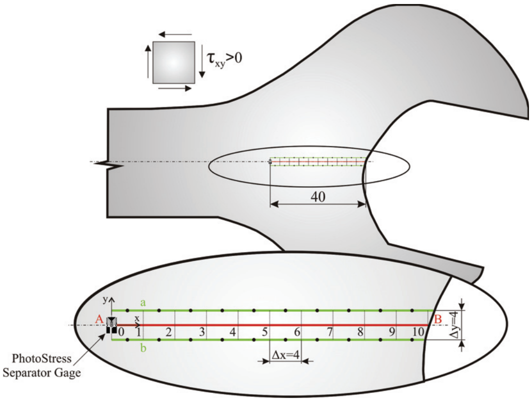

Fig. 9 *Points of separation by separation strain gage*

By use of separation strain gage PSG-01-06 with deformation factor k = 2,05 ± 5%, which was glued in point 0 by glue M-Bond 200 (Fig. 6) was determined sum of principal strains For the measurement was used static strain gage apparatus P-3500 and module 330 (Fig. 10). Sum of principal strains measured in point 0 is $\varepsilon_1 + \varepsilon_2 = 30.10^{-6}$.

For the separation by separation strain gage is necessary to determine in that point also difference of principal strains $\varepsilon_1 - \varepsilon_2$. This was determined in point 0 by program PhotoStress and its magnitude is $\varepsilon_1 - \varepsilon_2 = 610.10^{-6}$ [1].

Sum of principal normal strains $\varepsilon_1 + \varepsilon_2$ marked as $\Sigma\varepsilon$ and measured by strain gage as well as difference of principal strains $\varepsilon_1 - \varepsilon_2$ marked as S_p are included to following relations from which we have principal strains [6,7]

$$\varepsilon_1 = \frac{\Sigma\varepsilon + S_p}{2} = 320.10^{-6},\ \varepsilon_2 = \frac{\Sigma\varepsilon + S_p}{2} = -290.10^{-6}.$$

Fig. 10 *Measurement strain gage apparatus P-3500 with modul 330*

From the Hooke law then, after substitution of principal strains ε_1 and ε_2 we have principal normal stresses

$$\sigma_1 = \frac{E}{1-\mu^2}(\varepsilon_1 + \mu\varepsilon_2) = 53{,}769\,MPa,$$

$$\sigma_2 = \frac{E}{1-\mu^2}(\varepsilon_2 + \mu\varepsilon_1) = -44{,}769\,MPa.$$

For computation of normal stresses σ_x and σ_y in point 0 we have to know angle α between principal normal stress σ_1 and normal stress σ_x. Angle α is parameter of isocline going throught point 0. Parameter of isocline determined by PhotoStress in point 0 is $\alpha = 7{,}02°$. Normal stresses σ_x and σ_y in point 0 we get from relations:

$$\sigma_x = \sigma_1 \cos^2\alpha + \sigma_2 \sin^2\alpha = 52{,}298\,MPa,$$

$$\sigma_y = \sigma_1 \sin^2\alpha + \sigma_2 \cos^2\alpha = -42{,}298\,MPa.$$

After determination of magnitude of normal stress $\sigma_x = 52{,}298\ MPa$ is realized computation of separated values of principal normal stresses in further points of chosen region by the method of difference of shear stresses by program PhotoStress. In the process of separation is chosen in folder **Separation** the subfolder ***Shear difference method*** (Fig. 11). In this subfolder is chosen test in window Test, region in windows ***ROI*** and photograph of isochromatic fringes for analyzed loading in window ***Image***. Into the box ***Measured value*** σ_x is written value of normal stress σ_x determined in starting point 0 from previous measurement and successively is started computation of separated values of principal normal stresses by method of shear stress differences for points 1 to 10 of line region.

Magnitudes of normal stresses σ_x, σ_y and principal normal stresses $\sigma_1(\sigma_2)$, $\sigma_2(\sigma_3)$ in points 0 to 10 separated by method of shear stress differences in program PhotoStress are given in Tab. 2.

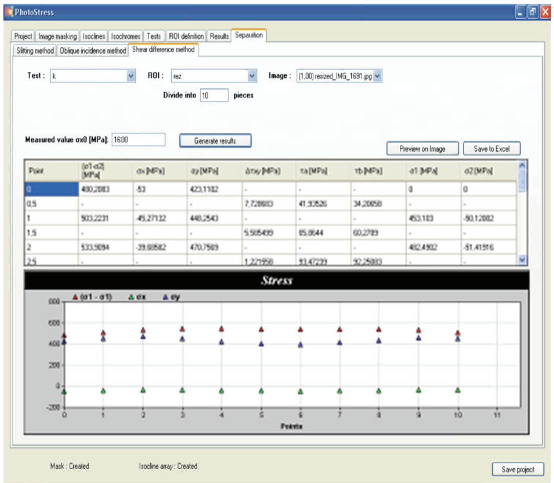

Fig. 11 *Output of program PhotoStress for separation by method of differences shear stresses*

Point of measurement	α	σ_x	σ_y	τ_{xy}	$\sigma_1(\sigma_2)$	$\sigma_2(\sigma_3)$
0	7,02	52,30	-43,30	11,95	53,77	-44,77
1	9,78	59,71	-32,05	16,31	62,52	-34,86
2	10,05	64,32	-17,67	14,99	66,98	-20,32
3	11,99	63,38	-4,34	15,06	66,58	-7,54
4	15,69	62,82	18,51	13,51	66,61	14,72
5	26,21	69,70	54,07	10,15	74,69	49,07
6	-10,68	65,92	91,36	4,97	92,30	64,99
7	7,96	57,26	114,86	-8,22	116,01	56,11
8	10,67	54,91	176,75	-23,79	181,24	50,42
9	13,24	43,60	221,48	-44,29	231,90	33,19
10	15,00	19,12	270,32	-72,52	289,75	-0,32

Tab. 2 *Stresses in analyzed points of line region*

SEPARATION OF PRINCIPAL NORMAL STRESSES BY METHOD OF OBLIQUE INCIDENCE

Determination of individual components of principal normal stresses of beam with notches by program PhotoStress, with using reflection polariscope M030 and application of method of oblique lightening is described in the following part of a paper.

For application of this separation method was applied on a steel specimen according to STN 11 523, with thickness 3 mm, shape, dimensions and character of loading given in Fig. 12, glued by two-component glue PC-1 photoelastic coating PS-1 with thickness 3,125 mm. Material characteristics of steel and photoelastic coating are given in Table 1.

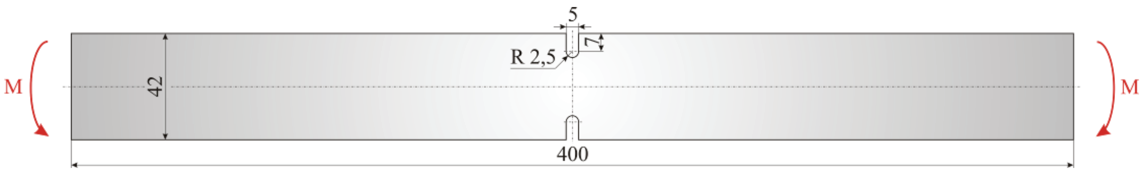

Fig. 12 *Shape, dimensions and character of loading of a beam with notches*

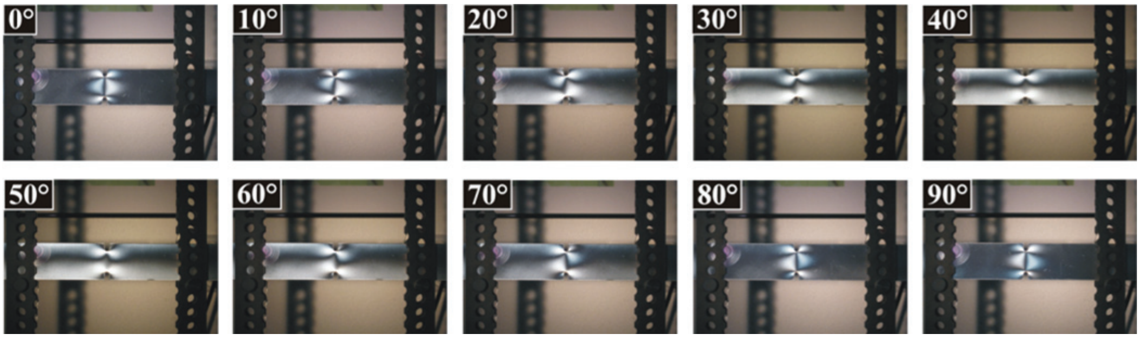

Fig. 13 *Shape, dimensions and character of loading of a beam with notches*

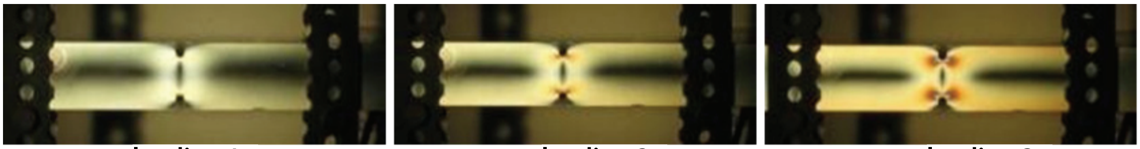

Fig. 14 *Isochromatic fringes for successive loading of beam*

Bundle of photographs of isocline curves (Fig. 13) gained by digital camera CANON A380 throught reflection polariscope M030 with angle parameters from 0° to 90° and 10° increment and isochromatic fringes (Fig. 14) serves as input for determination of directions and magnitudes of principal normal stresses in program PhotoStress.

After processing of photographs of isocline curves in program PhotoStress was drawn bundle of isocline curves (Fig. 15) and set of isostatic curves of the I-st and II-nd kind (Fig. 16) for whole analyzed area of coated beam. Isostatic curves represent stress paths or directions of principal normal stresses.

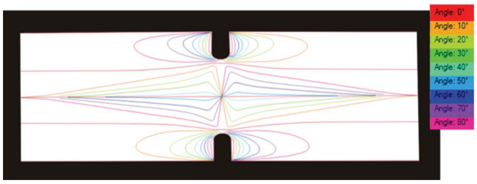

Fig. 15 *Bundle of isocline lines of parameters 0° to 90°drawn by program PhotoStress*

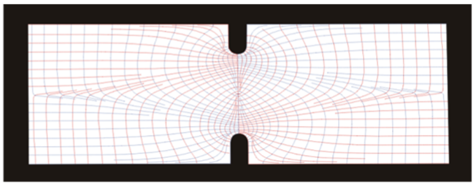

Fig. 16 *Bundle of isostatic lines of I-st and II-nd kind drawn by program PhotoStress*

Detrmination of principal normal stresses in beam with notches was accomplished in five points along line region (Fig. 17) in program PhotoStress. During computation was considered correction of fringe order for plane stress state.

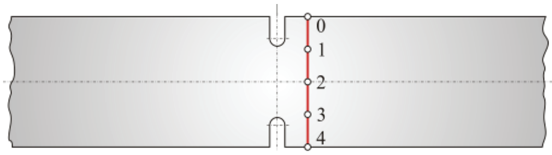

Fig. 17 *Line region*

In Fig. 18 is shown environment of application PhotoStress for separation method of oblique lightening.

Because of fact that there was seen starting birefringence during separation with using oblique lightening, it was performed correction of fringe order read during oblique lightening. Input values needed for accomplishing correction of fringe orders for oblique lightening N_θ are given in Tab. 3, where:

C_i - is value read from compensator without loading of object,

C_f - is value read from compensator after loading of object,

$\beta_{\theta i}$ - isocline parameter of higher principal stress of unloaded object,

$\beta_{\theta f}$ - isocline parameter of higher principal stress of loaded object,

$N_{\theta i}$ - order of isochromatic fringes before loading,

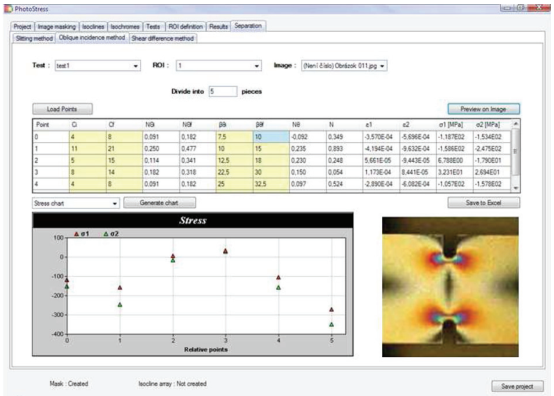

Fig. 18 *Environment for the method of oblique incidence in application PhotoStress*

$N_{\theta f}$ - order of isochromatic fringes after loading,
$N_{\theta kor.}$ - corrected fringe order for oblique lightening.

Correction of fringe order $N_{\theta kor}$. was performed by reading of vectors in program PhotoStress.
In Tab. 4 are given values of fringe orders before correction N and after correction $N_{\theta kor.}$, principal strains ε_1, ε_2 and principal normal stresses σ_1, σ_2 determined in points of investigated line region by program PhotoStress.
Graphical outputs of fringe orders N and charts of principal normal stresses σ_1 and σ_2 in investigated points of line region are given in Fig. 19a and Fig. 19b [3].

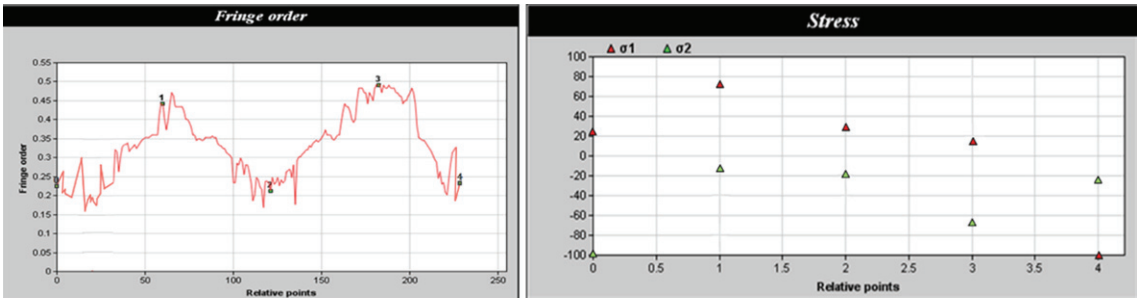

Fig. 9 *Graphical representation of charts: a) fringe orders N; b) principal normal stresses σ1 and σ2 determined by program PhotoStress*

Point of measurement	C_i [-]	C_f [-]	$N_{\theta i}$ [-]	$N_{\theta f}$ [-]	$\beta_{\theta i}$ [°]	$\beta_{\theta f}$ [°]	$N_{\theta kor.}$ [-]
1	8	36,5	0,182	0,830	-1	-5	0,651
2	12	22	0,273	0,500	35	55	0,342
3	15	33	0,341	0,750	-70	-85	0,486

Tab. 3 *Correction of fringe orders for oblique lightening*

Point of measurement	N [-]	$N_{\theta kor.}$ [-]	ε_1 [-]	ε_2 [-]	σ_1 [MPa]	σ_2 [MPa]
0	0,233	-	$1{,}419.10^{-4}$	0	22,928	0
1	0,442	0,651	$3{,}3531.10^{-4}$	$-1{,}632.10^{-4}$	70,187	-13,213
2	0,212	0,342	$1{,}577.10^{-4}$	$-1{,}386.10^{-4}$	26,804	-21,057
3	0,491	0,486	$1{,}570.10^{-4}$	$-3{,}428.10^{-4}$	12,511	-68,230
4	0,242	-	0	$-1{,}498.10^{-4}$	0	-23,856

Tab. 4 *Values of principal normal stresses determined in points along line region*

CONCLUSION

The authors show new possibilities of using PhotoStress method with application of program application PhotoStress.

From example of determination of magnitudes of individual principal normal stresses σ_1 *and* σ_2 on fork spanner or beam with notches by application PhotoStress with using reflection polariscope M030 and M040 as well as using separation method of differences of shear stress differences, method of using sseparation strain gage and method of oblique lightening is obvious that the program application substantially accelerates quantitative analysis of directions and magnitudes of principal normal stresses or principal strains and accordingly it spreads PhotoStress® method from laboratories into technical practice. Application will be enhanced for analysis of residual stresses by PhotoStress® method with using hole-drilling method and dynamic analysis with using stroboscope light and high-speed cameras.

Further enhancement of software application will be published on conferences and in journals.

ACKNOWLEDGEMENT

The article was based on the support of the Operational Programme Research and Development OPVaV-2009/2.1/03-SORO, application identifier 772253 entitled "Management Research Center of the technical, environmental and human risks for sustainable development of production and product engineering.

REFERENCES

[1] Z. BAKŠIOVÁ, Separácia hlavných pomerných deformácií na základe ďalšieho experimentálne určeného parametra pri metóde PhotoStress. Dizertačná práca, KAMaM, SjF TU Košice, 2010

[2] P. FRANKOVSKÝ, Využitie experimentálnych metód mechaniky pri určovaní zvyškových napätí. Dizertačná práca, KAMaM, SjF, TU v Košiciach, Košice, 2010

[3] A. KOSTELNÍKOVÁ, Určenie napäťových veličín pri metóde PhotoStress s využitím len polí izochróm a izoklín. Dizertačná práca, KAMaM, SjF,

[5] F. TREBUŇA, J. JADLOVSKÝ, P. FRANKOVSKÝ AND M. PÁSTOR, Abilities of New Software for PhotoStress Method. In: Experimentální analýza napětí 2010, Proceding - 48th International Scientific Conference, Olomouc: Palacky University Olomouc, 2010, ISBN 978-80-244-2533-7

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

[7] F. TREBUŇA, F. ŠIMČÁK, F.: Príručka experimentálnej mechaniky. Košice: TypoPress, 2007, 1526 s. ISBN 970-80-8073-816-7