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Implementation of correction coefficients relevant for photoelastic coatings into the PhotoStress software

Peter Frankovský[1,a], František Trebuňa[1,b], Ján Jadlovský[2,c], Miroslav Pástor[1,d] and Mária Kenderová[1,e]

[1]Technical University of Košice, Faculty of Mechanical Engineering, Letná 9
042 00 Košice , Slovak Republic

[2]TechnicalUniversityof Košice, Department of Cybernetics and Artificial Intelligence, Vysokoškolská 4, 042 00 Košice, Slovak Republic

[a]peter.frankovsky@tuke.sk, [b]frantisek.trebuna@tuke.sk, [c]jan.jadlovsky@tuke.sk, [d]miroslav.pastor@tuke.sk, [c]maria.kenderova@tuke.sk

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Abstract. Optical experimental method PhotoStress is based on the principle of birefringence that occurs on photoelastic coatings on the surface of an object subject to examination. However, photoelastic coating strengthens the examined surface; hence, strains that co-occur in the analysed object exhibit lower values than when no coating is applied. This is the reason for the implementation of relationships for correction coefficients into the PhotoStress software which is now being designed. These coefficients are supposed to eliminate discrepancies in gained values resulting from the impact of stiffness through applied photoelastic coating. Into the PhotoStress software were implemented correction coefficients for plane stress C_{PS}, one-side coated objects under bending stress C_B, two-sides coated objects under bending stress C_{B2}, shaft rotation C_t and pressure vessels C_N. The following paper includes explanations of particular types of corrections which were implemented into the PhotoStress software.

Introduction

In stress analysis through PhotoStress method a number of cases occurs when the thickness of photoelastic coating causes reinforcement. This effect needs to be taken into consideration otherwise we will not be able to reach accurate results. Such reinforcement through photoelastic coating is insignificant and can be ignored in situations when it comes to structural elements such as I-, H-, U-beams or box girders, heavy and massive cross sections, porous structures, casts etc. Reinforcement effect cannot be ignored neither in plane-stressed parts (pressure vessels, walls under plane loads) nor in cases of membrane stresses which occur even when low or near-zero bending loads are applied [5, 6, 7, 8].

With photoelastic coating applied to thin beams or boards subject to bending loads the particular coated part is reinforced and determined strain values need corrections. Reinforcement effect can neither be ignored in low-modulus structural materials (e.g. plastic materials) subjected to plane stress. Also here is the correction of calculations needed. As a result, correction coefficients must be implemented into software application PhotoStress.

The following part of the paper includes descriptions of correction types which are implemented into software application PhotoStress. Among these corrections are:

- corrections relevant to reinforcement effects of coatings at plane stress,
- corrections relevant to reinforcement effects which occur on one-side coated objects under bending load,
- corrections relevant to reinforcement effects which occur on two-sides coated objects under bending load,
- corrections relevant to reinforcement effects of coatings at torsional loads,
- corrections relevant to reinforcement effects of coatings applied to pressure vessels.

Corrections relevant to reinforcement effects of coatings at plane stress

Plane stress state can be found in structural elements such as shells and walls. These elements are loaded only in their centre line plane and are not subjected to additional bending moments. Pressure vessels with thin walls and other structural elements as well may be processed in the same way as in case of plane stress state. If this kind of structural element is loaded while coated with photoelastic coating, the applied coating has a reinforcing effect on this structural part and transforms a part of that loading. As a result, in tested object are determined strain values which are lower than if no coating were applied. Nonconformities which occur in metal structures resulting from reinforcement effect are insignificant and usually do not need to be taken into consideration. However, if the tested object is made from polymer material or some other non-metallic materials, the rate of nonconformities is high and correction is needed [7, 8].

In the event of plane stress state, correction coefficient relevant to reinforcement effects has the form as follows:

$$C_{PS} = 1 + E^* t^* , \qquad (1)$$

where C_{PS} represents correction coefficient by which the fringe order at plane stress state needs to be multiplied. In this way we get correct value of fringe order.

$E^* = \frac{E_c}{E}$ - relation of Young's modulus of photoelastic coating and Young’s modulus of tested object,

$t^* = \frac{t_c}{t}$ - relation of thickness of photoelastic coating and thickness of tested object.

Photoelastic coating transforms a part of load, which is in usual conditions transformed by the structure. Deformation rate that occurs in coated part is hence lower than actual deformation. Fig. 1 depicts deformations in the event of plane stress state [3, 4, 5].

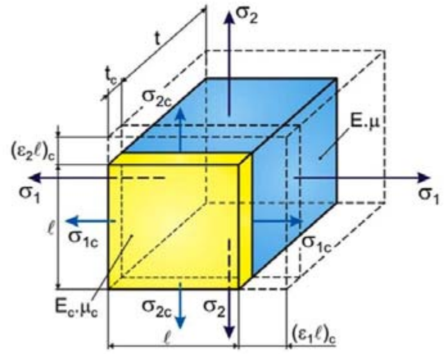

Fig. 1 Stress state and deformation in the structure and its coating in the event of plane stress state

Corrections relevant to reinforcement effect in one-side and two-sides coated object under bending loads

During bending loads applied to thin beams, boards or shells are the effects of photoelastic coating on structural element usually considerably lower than in the event of plane stress state. Correction is, hence, almost inevitably needed. The effect of coating on structural element under bending is rather complex. As a result, correction coefficient will solve three different effects:

- neutral axis of coated part moves in the direction of coated side,
- applied coating increases stiffness of elements and decreases bending deformation,
- the effect of strain gradient over the thickness of applied coating.

Software application PhotoStress enables us to identify fringe order in central-line plane of the coating. The coating is placed in bigger distance from neutral axis than the surface of tested element. The first two effects tend to decrease the identified fringe order. The third effect has rather increasing tendency, hence the values of fringe order are higher. All three effects are active simultaneously. However, they are influenced by Young's modulus, thickness of photoelastic coating and thickness of tested object [7].

Photoelastic coating can be applied to an object subject to bending in two ways:

- from one side – one-side coating of an object (Fig. 2a),
- from both sides – two-sides coating of an object (Fig. 2b).

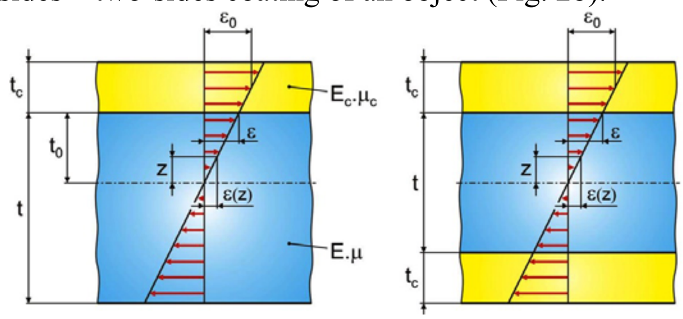

Fig. 2 Coating of an object under bending loads

Neutral axis of an object with thickness *t* and with photoelastic coating applied to one side of that coating will move in distance t_0. Its value can be derived from relation

$$t_0 = \frac{t}{2}\frac{1-\frac{E_C}{E}\cdot t^{*2}}{1+\frac{E_C}{E}\cdot t^{*2}}. \tag{2}$$

Correction coefficient relevant to bending C_B is defined while considering the condition which presupposes that bending moment in the cross section of a photoelastically coated board is the same as in board without coating being applied to it [7].

From the above-stated condition we can derive relation for correction coefficient relevant to one-side coated object subject to bending.

$$C_B = \frac{1}{1+t^*}\left[1+2t^*\left(2+3t^*+2t^{*2}\right)\frac{E_C}{E}+t^{*4}\cdot\left(\frac{E_C}{E}\right)^2\right]. \tag{3}$$

Correction coefficient for two-sides coated object has the following form

$$C_{B2} = \frac{1}{1+t^*}\left[1+2t^*\left(3+6t^*+4t^{*2}\right)\frac{E_C}{E}\right]. \tag{4}$$

Corrections of reinforcing effects during torsional loads

In strain-stress analysis of a photoelastically coated shaft under torsional loads we notice similar effects as during bending load applied to boards. Shear stress gradient differs in values from zero, and mean stress values are higher than strains identified on the surface of the shaft. Coating which is applied to the surface of the shaft increases its stiffness. Assuming that torsion moment transformed by the shaft without any coating is the same as when coating is applied, correlation coefficient can be expressed as follows

$$C_t = \frac{2}{1+\frac{R_c}{R}}\left\{1-G_c\left[\left(\frac{R_c}{R}\right)^4-1\right]\left(G\left[1-\left(\frac{r}{R}\right)^4\right]\right)^{-1}\right\}, \tag{5}$$

where r represents inner radius of the shaft, R is outer radius of the shaft, R_C is outer radius of photoelastic coating, G_C is the modulus of elasticity during shearing loads applied to coating material and G is the modulus of elasticity during shearing loads applied to the material of the shaft.

Fig. 3 depicts individual shaft materials and their correction coefficients relevant to torsional loads while taking into consideration relative thickness t^*.

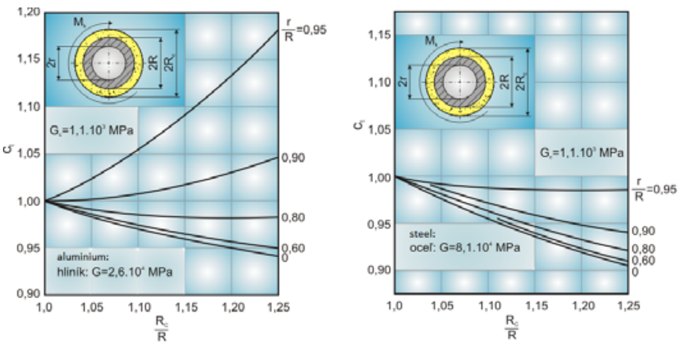

Fig. 3 Correction coefficients during torsional loads on shafts

Corrections relevant to reinforcement effects on the coating of a pressure vessel

PhotoStress® can be applied in strain analysis of pressure vessels too. Reinforcement effect of the coating is present in form of lower magnitudes of both elements of deformation. Correction coefficient C_N has the following form

$$C_N = \frac{1}{\dfrac{2\left(1-2\mu+\frac{R_c}{R}\right)(1-\mu)}{\left[1-2\mu+\left(\frac{R_c}{R}\right)^2\right]+\frac{E_c}{E}\dfrac{\left(\frac{R_c}{R}\right)^2-1}{1-\left(\frac{r}{R}\right)^2}\left[1-2\mu+\left(\frac{r}{R}\right)^2\right]}-\dfrac{1-2\mu}{1+\frac{E_c}{E}\dfrac{\left(\frac{R_c}{R}\right)^2-1}{1-\left(\frac{r}{R}\right)^2}}} \tag{6}$$

Fig. 4 depicts relations of correction coefficients relevant to pressure vessels which are made from aluminium and steel. Taken into consideration are geometry of the pressure vessel and photoelastic coating.

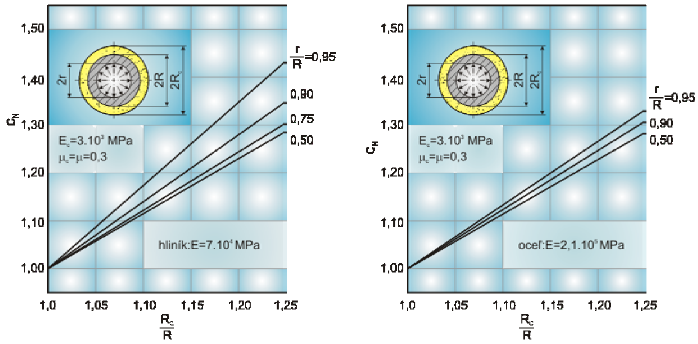

Fig. 4 Correction coefficients in pressure vessel

Implementation of correlation coefficients into software application PhotoStress

The principal of software application PhotoStress is the evaluation of colour in particular pixels of the image which depicts colourful isochromatic fringes. To each pixel is assigned *RGB* colour value, which represents relative intensity of red, green and blue colour. The application then transforms colour elements from *RGB* colour space into the elements of *HSV* colour space. This transformation needs to be carried out since the application works with *H* value of *HSV* colourful space in order to calculate isochromatic fringe order *N*. When the value of fringe order *N* is set, the application then determines the differences in principal strains and principal normal stresses [1, 2]. This calculation is based on the following relations

$$(\varepsilon_1 - \varepsilon_2)_C = N \cdot f \tag{7}$$

$$\sigma_1 - \sigma_2 = \frac{E}{1+\mu}(\varepsilon_1 - \varepsilon_2) \tag{8}$$

Individual magnitudes of principal strains and principal normal stresses are determined through appropriate separation methods.

When the above-mentioned types of loads are applied to photoelastically coated objects, reinforcement effects occur. If no correction coefficients are used, these effects tend to introduce inaccuracies in gained values. These inaccuracies can be reduced through implementation of an appropriate correction in the folder *Tests* where we select *Correction* (Fig. 5) [2].

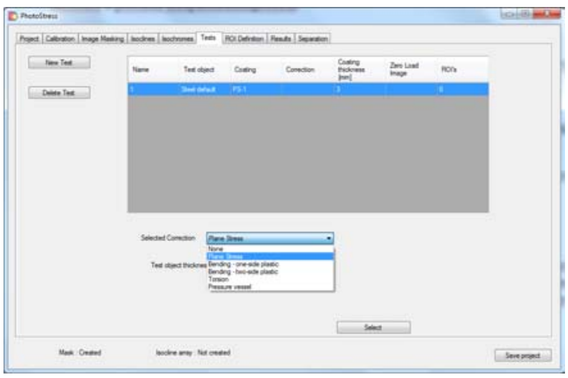
Fig. 5 Folder in software application PhotoStress for selection of correction type

Relations (1), (3), (4), (5) and (6) are implemented into the software application PhotoStress, which are relevant to correction coefficients while considering the type of loads and photoelastic coating. Correction coefficients determine the relation of actual deformation and deformation which was identified on the surface of tested object. Actual difference of principal strains $(\varepsilon_1 - \varepsilon_2)$ on the surface of tested object is calculated in PhotoStress application by means of correction coefficient C_i and from the difference between principal strains $(\varepsilon_1 - \varepsilon_2)_C$ in photoelastic coating, which is based on the following relation

$$(\varepsilon_1 - \varepsilon_2) = C_i (\varepsilon_1 - \varepsilon_2)_C \,, \tag{9}$$

The difference between principal strains $(\varepsilon_1 - \varepsilon_2)_C$ is in photoelastic coating determined from the field of isochromatic fringes.

Summary

Software application PhotoStress, which is still being improved, will provide simple and quick quantification of directions and magnitudes of principal strains and principal normal stresses while using the principal of reflection photoelasticity or, possibly, of PhotoStress® method. The correction of initial birefringence will be implemented into software application PhotoStress. The results of these measurements will be published in various journals and in future conferences.

Acknowledgement

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