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LUMINESCENT POWDER TECHNIQUE IN ELECTRONIC SPECKLE PATTERN PHOTOGRAPHY

For the generation of speckle images, a luminescent powder applied in a small amount to the sample surface and stimulated by UV radiation was used. We obtained fine-grained speckle patterns with very high contrast and small size of spots, The shape of the single speckle, unlike laser method, is circular, which is important for the effectiveness of the used digital image analysis methods. The measurements of displacements and deformations were made by use of digital image registration and its analysis using correlation procedures. The results are presented in the form of bitmaps, tables and graphs. The developed method was tested on flat wood specimens subjected to three-point bending.

Keywords: speckle metrology, elektronic speckle, ESPI, white light speckle photography, experimental strain analysis, analize of speckle pattern, speckle pattern, luminescent powder

INTRODUCTION

The laser speckle analysis of deformations of structural elements is known from the 80s of the last century [2-6, 10, 11] and it is always connected with a measurement error resulting from the rotation or deformation of the analysed surface. The speckle pattern recorded in laser light is spatial and during loading of the object it performs two movements simultaneously:

- translatory motion related to the linear displacement of the analysed part of the object's surface,
- rotary motion associated with the rigid rotation of the body and the local deformation of its surface.

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The linear displacement of the speckle registered by the camera is a superposition of displacements resulting from both movements. The difference between the real vector displacement of the selected point and its image recorded by the camera is proportional to the vector product $\Delta s = \delta \times \mathbf{d}$ of the local rotation angle δ and the local defocusing vector **d**. This is illustrated in Fig. 1.

The displacement's vector "s" recorded by the CCD camera is a view on the object plane as the sum of vectors **s** and Δ**s**. Regardless of the errors discussed above the spatial character of speckle structures generated in laser light leads to blurring of recorded images and lowering their contrast, which may result in a high level of random errors associated with the numerical processing of speckle images.

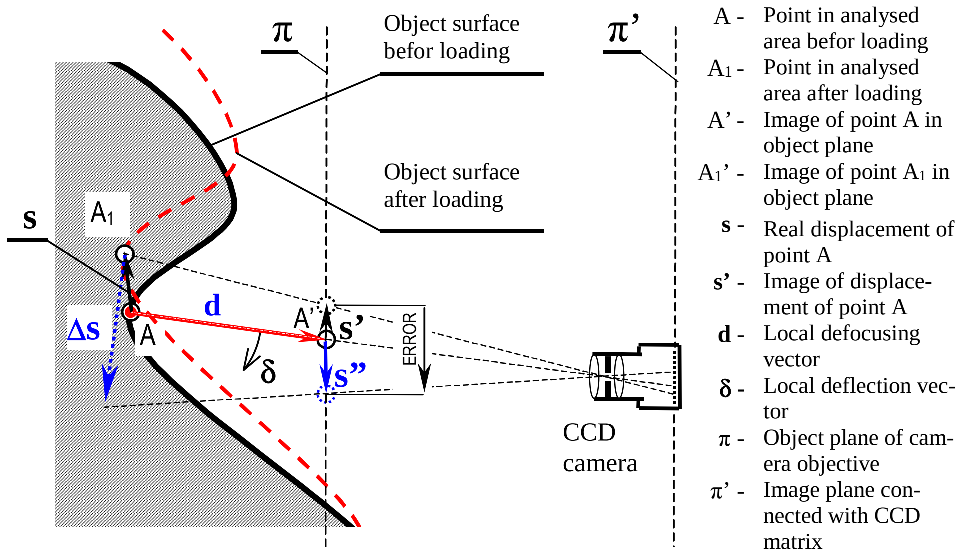

Fig. 1. Error recorded by the camera of the mapping of the actual displacement of the selected point A. It was caused by the camera's focusing and the rotation of the coherent speckle structure by the angle **δ.**

Numerical analysis of speckle positions in coherent method is also hampered by irregular shapes of speckles. This is visible in Figure 2.

The uniqueness and complexity of the speckle shapes materially impedes both initial and final selection of features used for tracking position of selected area of film frame or bitmap.

Problems related to the separation of linear deformations or strain and problems related to the industrial application of laser metrology have resulted in the development of methods of speckle metrology in white light [12-14, 20, 24]. One of the variants of this group of measurement methods is the technique of reflective powders developed by J. Pisarek [7, 8], based on spraying of reflective powder (most preferably dactyloscopy powder) on the surface of tested object. The disadvantages of this technique are:

- necessity of blackening the surface of the object before applying dust to it,
- relatively low durability of the dust layer,
- necessity of using strong light sources with a fairly high spatial coherence.

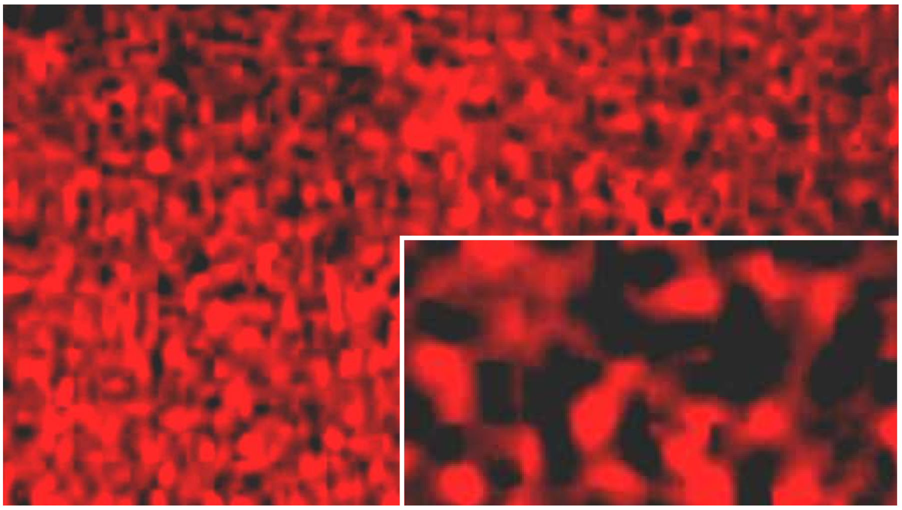

Fig. 2. Speckle pattern generated by the wood surface in the light of the GaAS laser

In order to obtain a high contrast of speckle structures and to eliminate uneven illumination of recorded images, it is necessary to work in the dark, which may be troublesome in industrial or range environments. An alternative to powder technology [7, 8] is the use of special reflective paints containing salt crystals (C.Forno [12]) or glass microspheres. The preparation and proper use of these paints is quite cumbersome and requires practical experience. The luminescent powder technology proposed in this article is much easier to use in practice. The analysis of speckle pattern (and specklegrams) can be making using analogue methods, like optical Fourier processors [3, 6-8, 14, 20, 24] or digitally with the use of different techniques of the image analysis. In the literature one can find a great deal of examples of uses of the digital analysis application e.g. works [9, 18, 19, 22, 23, 30-37]. The number of original works concerning of the methodology of research [25-29, 38] is evidently smaller. Measuring techniques presented in this article were checked experimentally within the framework of the work [1] realised in the Institute of Techniques and Systems of Safety in the Laboratory of Speckle Metrology, Holography and the Optical Information Processing and partially in the private laboratory of the experimental mechanics founded by

J. Pisarek. Calculations were performer by use of the author's programming [15, 17] developed by K. Suprynowicz.

1. PRINCIPLES OF EXPERIMENTAL TECHNIQUE

The essence of the proposed techniques is the sprinkling of luminescent or phosphorescent powders into object's surfaces. Authors propose the following dust application techniques:

- powder spraying and gravitational descending on a dry surface of the element,
- powder spraying and gravitational descending on the surface of the element covered with wet paint, oil or other sticky substance,
- spraying the surface with a clear varnish containing a luminescent active pigment.

Depending on the type of luminescent or fluorescent powder used, the surface of the element is irradiated with UV light or visible light with a wavelength shorter than the light emitted by the dust. In the case of fluorescent powders the image exposure was done immediately after lighting. In second case with using of luminescent powders - exposure was done in during of a photoexcitation so an addition of UV filter to the camera's optical pathway was necessary.

1.1. Preparation of specimens surfaces

The tests were carried out on flat wooden specimens. Obviously, the same methodology can be used for any structural material and elements of any shape. A hair sprayer was used to spray the powder. Construction of a simple sedimentation chamber was required to obtain an even distribution of marker particulate. The device is shown in Fig. 3. The chamber should have dimensions much larger than the size of the sputtered element. Authors used cardboard boxes to create a simple and effective chamber.

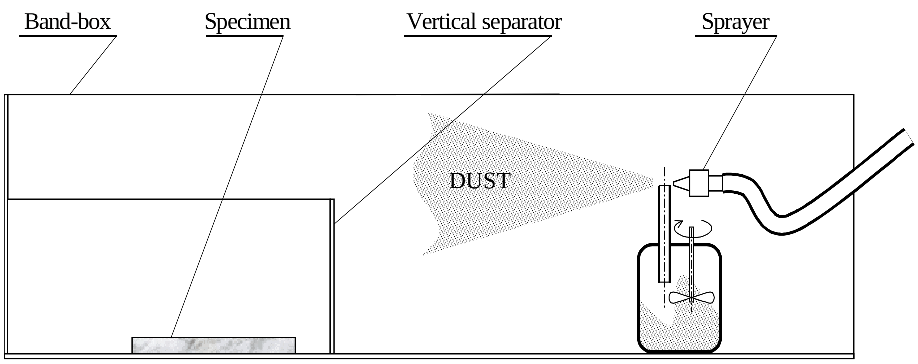

Fig. 3. Sprayer used to cover a wooden specimen

In use of non-transparent coating technology, black acrylic spray varnishes were applied following the manufacturer's instructions. The CAPON clear lacquer (nitro-cellulose lacquer) was applied simply with a brush.

The preparation of the luminescent varnish required the following sequence of operations

1. Pigment distribution in a large amount of solvent (about 0.5 g / l)
2. Dilution of the CAPON varnish in the ratio 4: 1
3. Introduction of varnish to the sprayer or atomiser
4. Spray painting

For the preparation of luminescent varnishes, transparent resins for UV and solvent suitable for their dilution should be used. The best results are obtained by using a methyl methacrylate (plexi) diluted with chloroform with the addition of a small amount of plasticizer (N-N butylphthale) as a resin.

A typical speckle pattern obtained by spraying luminescent powder on wet lacquer layers is shown in Figure 4. Regular shapes of spots deserve the attention, because they enable the application of such tools of the image analysis which in case of laser speckle pattern would be very troublesome.

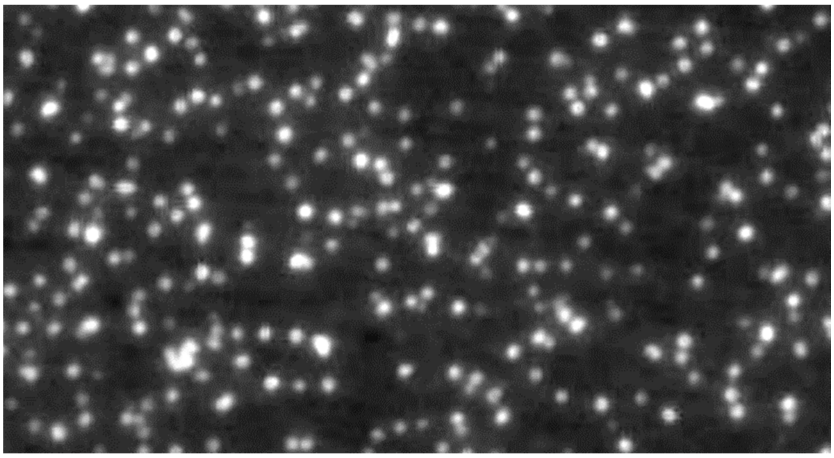

Fig. 4. Structure obtained by spraying by luminescent powder (source [1])

The homogeneity of the background is a second advantage of speckle pattern obtained by luminescent or phosphorescence techniques.

1.2. Registration of the image

The scheme of speckle image capture system is shown in figure 5.

The specimen was illuminated at an angle of about 30^0 with a UV reflector. The camera and the loading system were placed on long strip footing. The diagram of the loading system is shown in figure 6.

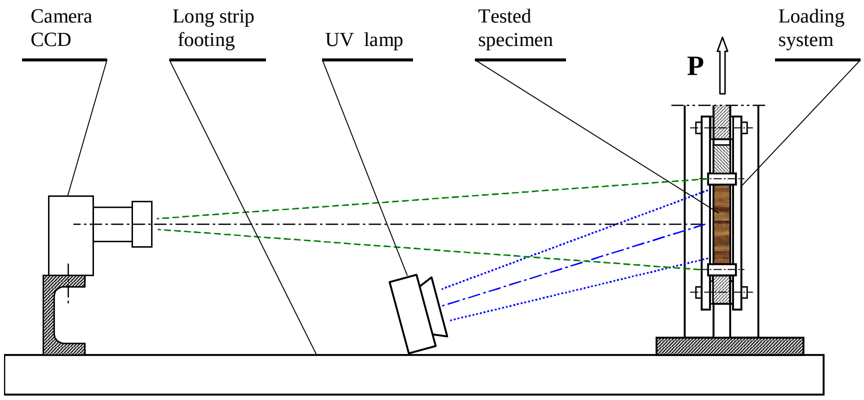

Fig. 5. Scheme of registration system

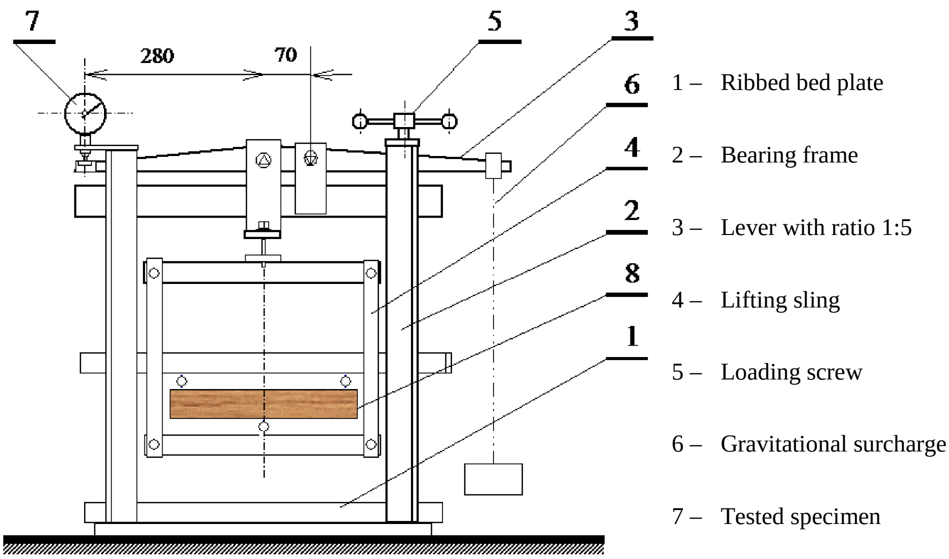

Fig. 6. Configuration of loading system (source [1])

1.3. Loading system

In the experiment the loading system from elastooptic polariscope was used. He enabled the realisation facultative flat states of the strain. The load was realised in a kinematics manner by means of the screw (5). The value of displacement of selected point of the lever (3) was measured with the accuracy about 0.01 mm by means of the dial gauge (7). This made possible to determine the value of displacement of the force application point on accuracy of 0.002 mm. Unfortunately, the low stiffness of the lifting sling and the low stiffness of the benches on which the entire loading system has been mounted cause additional and uncontrolled movements of the sample relative to the reference system connected with the camera. Compensation of this effect (possible on the way of numerical processing of registered bitmaps) is effective for determination of strain only. Unfortunately, the compensation of systematic errors appearing in measurement of movements is here not possible.

For achievement of this purpose the measurement of movements of apparent elements of the lifting sling would be necessary. Unfortunately authors of this work did not perform this additive measuring.

1.4. Image analysis

Displacement and strain distributions were calculated using two-dimensional Digital Image Correlation software. Software utilises a two-step approach, with first step using rectangular image subset, that is tracked on concurrent images with subpixel precision using bicubic interpolation. Tracking is conducted by a brute force search algorithm maximising Pearson correlation coefficient between two images. Speckles are used as subset centres. First step results in approximate displacement map. Second step of the algorithm begins with creation of triangle mesh with vertices placed on individual speckles. Pearson correlation coefficient is again maximised, this time using algorithm similar to simulated annealing. Strain distribution is derived from the resulting displacement map by calculating finite differences. Strain distribution is then filtered by Gaussian kernel filter.

Regular shapes of speckles obtained with the use of luminescent powders give the possibility of image processing also using the algorithms based on the click theory and the theory of Markov random fields [16]. These methods allow a very significant reduction of accidental error and improve the measurement accuracy by at least an order of magnitude. Unfortunately, they are sensitive to the occurrence of the common errors. Therefore, they should be used in conjunction with correlation methods.

2. APPLICATION IN THE TEST OF COMPOSITE SPECIMENS

The test method were carried out on wooden specimens with the dimensions 250x50x18 mm under three point loading according to the scheme shown in Fig. 7.

Fixed points should exhibit not the true displacements of selected specimen area but present an additional rigid displacements of the recorded image, relative to the camera coordinate system. These movements are a sum of movements related to the deformation of the sample and movements connected with of her rigid turn, resulting from the foldability of the loading arrangement. The second from mentioned components of displacement can be compensated by software in the data analysis process. An additional source of discrepancies in the experimental results in relation to the theoretical expectations was the non-linearity of the elastic characteristics of wood, and in the case of large loads also its plastic deformations.

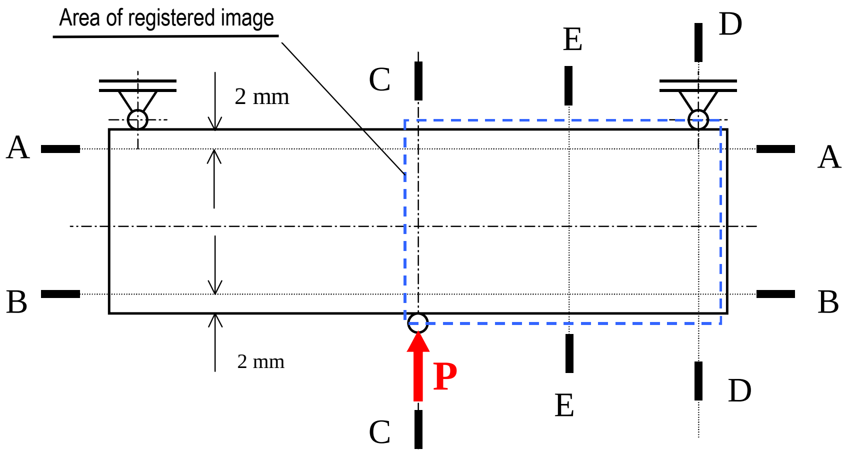

Fig. 7. Diagram of sample loading and position of cross sections for which the deformation distribution are presented in the following part of the article (Figures 11 and 12)

2.1. Whole field results of displacement measuring

The results of the displacements and strains analysis can be presented in whole field in the form of contour diagrams or bitmaps, on which a given value of displacement or strain corresponds to a particular colour of the image. This article adopts a scale in which the smallest value corresponds to the blue colour (the shortest wavelength of light) and the highest value is the red colour (the longest wavelength). Figures 8-10 show a linear mapping of the measured value of the wavelength assigned to a given measuring point. Obviously, due to the requirements of the printing process particular colours are simulated using the superposition of the so called primary colours.

Figure 8 shows colour maps of horizontal and vertical linear displacement, which was measured in a direction perpendicular to the direction of observation.

They conform to the load by the central force P which causes the vertical displacement to be set at the point of its application and accord to the movement of the point of force application equal approx. 4 mm. The dark area near the point of application of force is the shadow of the roller, through which the force is applied to the sample. It is visible due to the angular lighting (below at an angle of about 30^0).

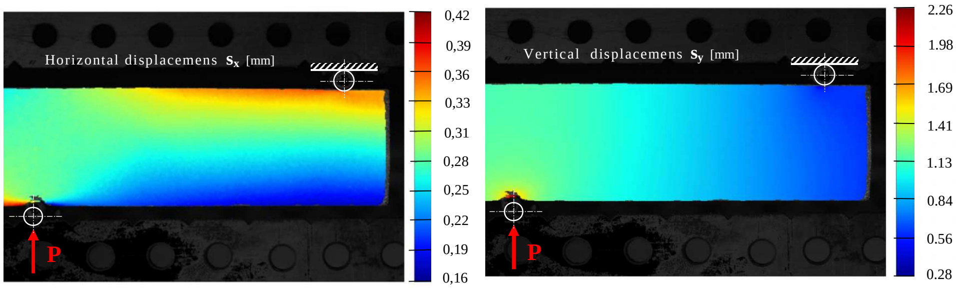

Fig. 8. Experimentally obtained colour maps representing distribution of displa-cements of the wood specimen surface during three-point bending

The following diagrams show the strain distributions ε_x (Fig. 9) and ε_y (Fig. 10) corresponding to the same load. All plots were prepared based on the analysis of the same pair of speckle images, i.e. the image recorded before and after loading the specimen. Fig. 9 shows the characteristic shape of the deformed zone, called "dog bone" in the jargon of people dealing with the strength of materials and with the fracture mechanics. It is characteristic for areas that are plastically deformed. The figure also shows some irregularities in the strain distribution that may be related to the structure of the material being tested These effects will be more clearly visible in point-by-point analysis, the result of which in selected sections is shown later in the work (Figs 11-12).

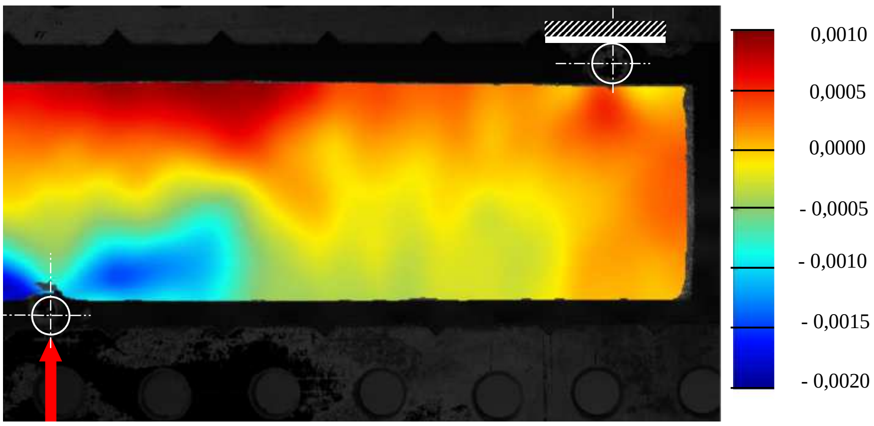

Fig. 9. Bitmap representing distribution of strain ε_x in whole field displacements (source [1])

The distribution of deformations ε_y visible around the point of application of force (Fig. 10) resembles the distribution of equivalent stresses known from the classic elastic theory, calculated according to the Mohr hypothesis.

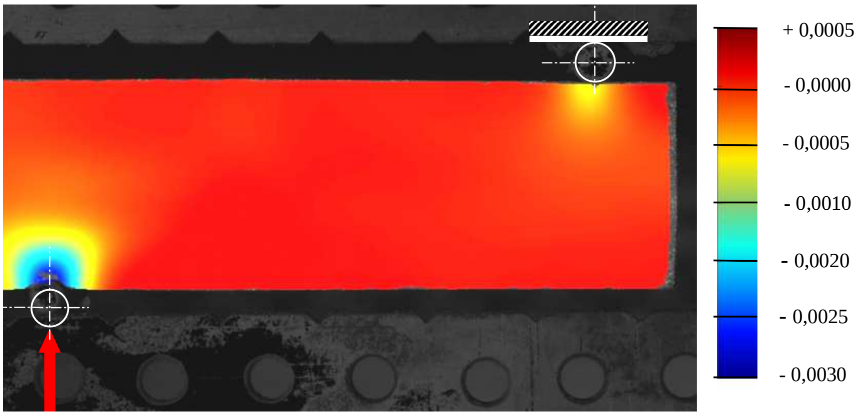

Fig. 10. Bitmap representing distribution of strain ε_y in whole field (source [1])

2.2. Strain distribution in selected cross-sections

On figure 11 the deformation distributions corresponding to different values of the shift of point of force application, and resultative different loads were compared. It quite unexpectedly turned out that the deformations measured locally are not proportional to the load and change irregularly along the cross-section. This is undoubtedly due to the nature of the material used for the tests, which is not linear-elastic, and, moreover, has a significant dispersion of local properties. So what is the sense to performing the engineering calculations with FEM, where the so-called simplifying assumptions are evidently leading to false results?

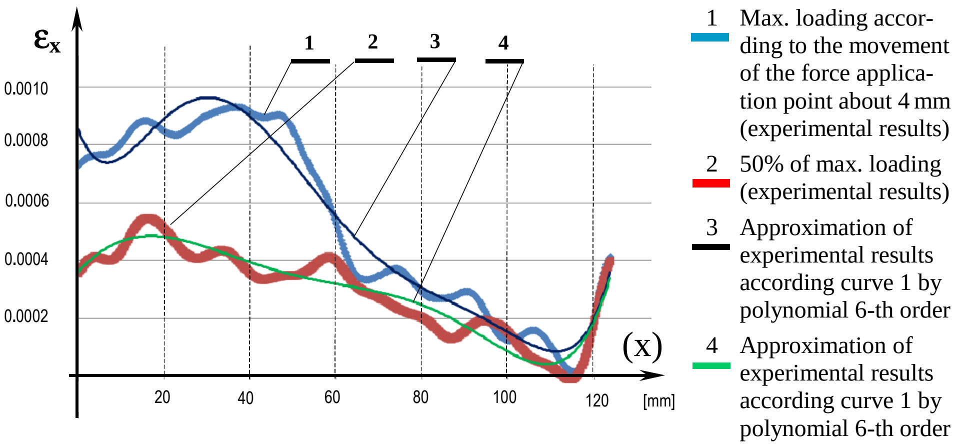

Fig. 11. Distribution of linear strains ε_x along the A-A section from fig. 7 (date from [1])

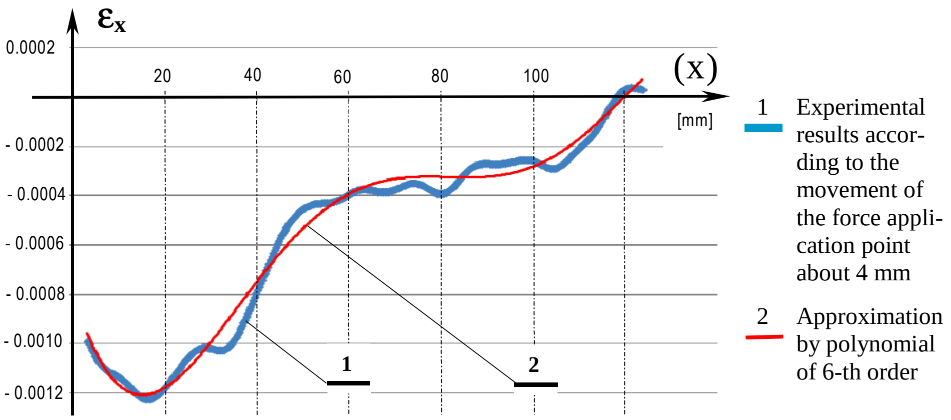

Fig. 12. Distribution of linear strains ε_x along the B-B section from fig. 7 (date from [1])

The graph shown in Fig. 12 shows only a few percent fluctuations of locally measured values (presented by a blue-green curve) around average values (red curve). Drastic differences in the course of diagrams of strains measured relative to perpendicular axes suggest a clear effect of the positioning of the composite fibres on the measurement result. Thanks to the measurement technique described in the article, it is possible to experimentally verify the actual impact of numerical errors (especially FEM calculations) on computational errors and validation of the software used.

CONCLUSIONS

The technique of speckle photography based on the use of luminescent powders is insensitive to angular displacements and angular micro-deformations of the tested object. It can be used on any elements without the need to blacken them. The phosphor may be applied by sputtering or introduced into the outer layer of the varnish coat. The second of presented techniques makes the method proof to atmospheric factors and its effective also in open area or range conditions. Due to the separation of pigment grains and their small size the luminescence technique combined with numerical image processing based on correlation techniques allows to achieve a resolution of several dozen μm are used. At the same time, the regular circular shape of the speckles creates favorable conditions for the use of image analysis techniques based on the theory of Markov random fields and clique theory, which should increase the measurement accuracy by an order of magnitude.

The simplicity of technology, a very wide measuring range and the ability to analyze deformations at very small measuring bases predestine the technique described for use as a basic experimental way of validating numerical engineering programs, including FEM programs. In the case of using varnish coatings, an additional argument in favor of the use of the measurement technique described in the article for validation and technical inspection is random and practically unique spatial distribution of spots recorded on a bitmap, which makes it practically impossible to make undetectable falsifications. An additional argument for the widespread use of the described technique supplemented with a possibly more extensive data analysis system is availability and a very low cost of measuring equipment and consumables.

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ZASTOSOWANIE PROSZKÓW LUMINESCENCYJNYCH W CYFROWEJ FOTOGRAFII PLAMKOWEJ

Do generacji obrazów plamkowych wykorzystano proszek luminescencyjny naniesiony w niewielkiej ilości na powierzchnię próbki i pobudzany do świecenia promieniowaniem UV. Uzyskano drobnoziarniste struktury plamkowe (speckle pattern) o bardzo wysokim kontraście i małym rozmiarze plamek, których kształt w przeciwieństwie do speckli laserowych jest kołowy, co ma istotne znaczenie dla skuteczności zastosowanych metod cyfrowej analizy obrazu. Pomiaru przemieszczeń i odkształceń dokonano poprzez cyfrową rejestrację obrazu i jego analizę przy użyciu procedur korelacyjnych. Wyniki zostały przedstawione poglądowo w postaci bitmap oraz w sposób bezpośredni w postaci tablic i wykresów. Opracowana metoda badawcza została przetestowana na płaskich próbkach drewnianych poddanych zginaniu trójpunktowemu.

Słowa kluczowe: metrologia plamkowa, speckle elektroniczne, fotografia plamkowa w świetle białym, eksperymentalna analiza odkształceń, analiza obrazów plamkowych, Technika proszkowa, proszki luminescencyjne

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