Optical Experimental Methods and their Implementation and Comparison in Conditions of Experimental Stress Analysis

P. Frankovský[1,*], P. Sivák[1], I. Delyová[1], J. Kostka[1]

[1] *Department of Applied Mechanics and Mechanical Engineering, Faculty of Mechanical Engineering, Technical University of Košice, Letná 1/9, 042 00 Košice, Slovakia*

[*] *peter.frankovsky@tuke.sk*

Abstract: This paper deals with a brief overview of the application and mutual comparison of optical experimental methods for the analysis of deformations and mechanical stresses. In addition to the now traditional PhotoStress optical method, such modern methods as the digital image correlation, holographic interferometry, digital speckle interferometry, digital speckle shearography, including their various special modifications, etc., also come to the fore. These methods find their specific application as sophisticated non-contact methods mainly in the development of new methods for determining deformations, stresses and material characteristics, mainly in the field of fracture mechanics, residual stresses, analysis of elements in the elastic-plastic area of deformations, etc. The paper also presents related specific application examples, respecting the technical and software equipment of the experimental workplace of the Department of Applied Mechanics and Mechanical Engineering, Faculty of Mechanical Engineering, Technical University in Košice. These examples formed part of practical tasks or research programs for the development of new experimental mechanical methods.

Keywords: optical experimental method; PhotoStress; digital image correlation; holographic interferometry; digital speckle interferometry.

1 Introduction

Optical experimental methods (OEM) are an integral part of the analysis of deformations and stresses of structural elements and entire structures. They exist in addition to today's classical analytical, modern numerical methods and, of course, in addition to other experimental methods, such as tensometry, the method of brittle varnishes, etc. The above 3 fundamental approaches to experimental analysis of stresses (EAN, ESA) and deformations coexist in symbiosis on the basis of mutual verification, comparison and complementation. At the experimental workplace of the Department of Applied Mechanics and Mechanical Engineering, Faculty of Mechanical Engineering, Technical University in Košice, they found their application not only in teaching, but also in the field of scientific research and also in conditions of engineering practice. In addition to the clearly classic or already relatively widespread OEMs, such as the Moiré method of mechanical-optical interference, photoelasticity or PhotoStress, sophisticated optical methods such as digital image correlation, holographic interferometry, digital speckle interferometry, digital speckle shearography, including their various special modifications, etc., also come to the fore [1–7].

2 General characteristics and application of OEM

The essence of OEMs for the analysis of mechanical stresses and deformations, the applied physical principle and the area of operation was and is determined by gradual development of engineering and technology. They are based on different specific principles, are at different levels of development, have their specific focus and application. Their common feature is that they are either partially contact or completely contactless and are based on different properties of electromagnetic waves and their interference. The application of OEMs in experimental mechanics is advantageous mainly by contactless nature, variability and a high degree of processing of measured, currently practically completely digitized data. They typically have a high measurement sensitivity and often allow direct measurement, which does not require further analytical or numerical processing of the results. OEM finds application in fracture mechanics, research of composite and other modern materials, analysis of residual stresses, determination of local elastic-plastic deformations under cyclic stress, biomechanics, high-speed applications, vibration analysis, etc.

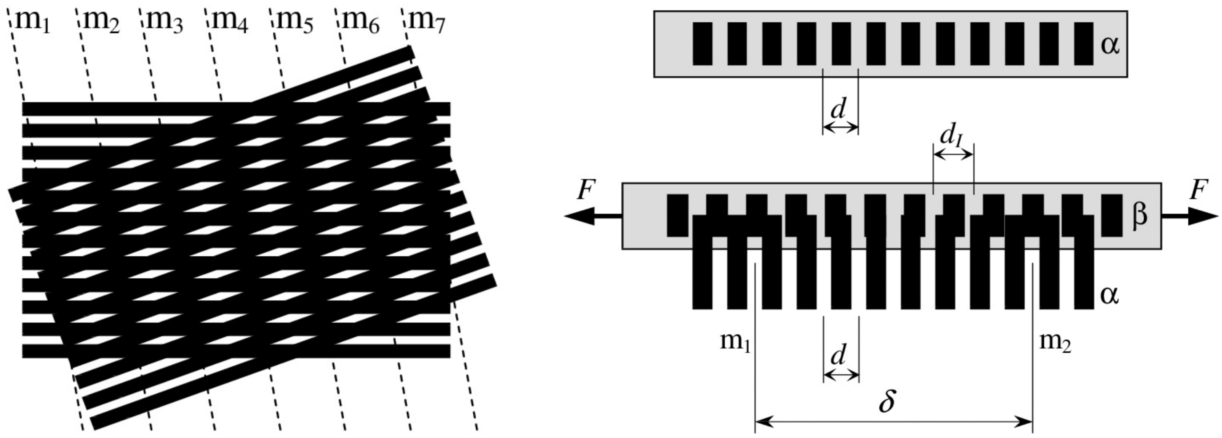
Of course, as with any experiment, OEMs are relatively time-consuming and technically demanding compared to other types of modeling and simulations. On the other hand, they can take actual physical conditions of the analyzed object into account.

Another general feature and, at the same time, a disadvantage of practically all OEMs is that their application, due to the principle and technical means used, is limited to relatively sterile laboratory conditions in practical implementations. They are generally unsuitable for difficult real conditions of structures in the field with significantly negative disturbing influences and for the analysis of dynamic events in general with a stochastic character.

3 Relevant OEMs today and examples of their use

3.1 Moiré mechanical-optical interference method

Due to the comprehensive overview and completeness, the Moiré mechanical-optical interference method can also be mentioned in part within the OEM. Moiré light effect with visible stripes is created by overlapping two optical gratings or rasters (Fig. 1a with Moiré stripe lines m_1 to m_7). By moving the original raster and the new deformed raster relative to each other (Fig. 1b) it is possible to approximately detect deformations on the surface of a loaded and deformed object. The application and extension of the Moiré method is currently very rare due to its limited possibilities.



(a) Overlap of two grids (rasters) with visible Moiré stripes m_1 to m_7.

(b) Overlap of two Moiré rasters: Original (undeformed) α and new (deformed) β.

Fig. 1: Grids in the Moiré mechanical-optical interference method.

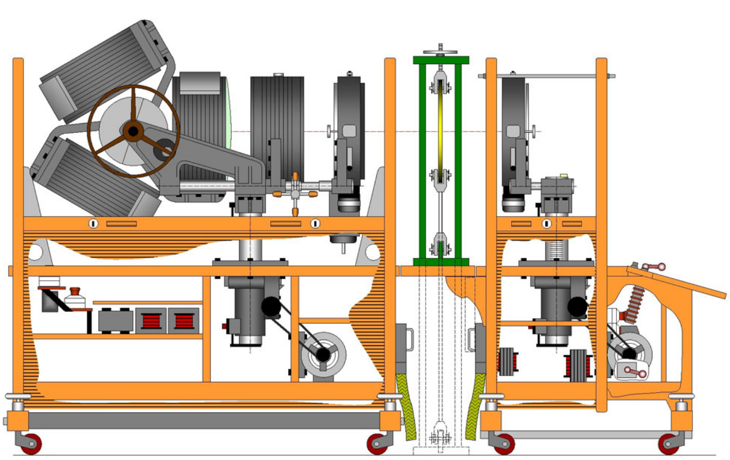
3.2 Method of transmission and reflection photoelasticity

One of the historically first and, at the same time, now classic OEMs is the transmission or reflection method (PhotoStress) or planar or spatial photoelasticity. It is based on the use of the properties of polarized light and the capabilities of some transparent, optically sensitive materials. At present, these are materials based on epoxy resins. These materials change from optically isotropic to temporary optically anisotropic under load and thus simultaneous deformation by a change in the refractive index due to a change in the speed of light propagation in the respective direction. The result is the emergence of observable, registrable and measurable interfering optical structures, so called isolines (optical interpretation), related either to the magnitude or direction of the respective deformations and mechanical stresses (interpretation of mechanics). Thus, by methods of photoelasticity, it is generally possible to determine magnitudes and directions of main relative elongations and main normal stresses, as well as the bevels and shear stresses at discrete points or on a certain surface. It is possible to identify immediately and relatively easily, in particular, the maximum circumferential stresses at the unloaded edges of the component. The method is therefore suitable for distinguishing the magnitude of nominal stress, concentrations and gradients of stresses and strains, including the identification of entire areas with high or low stress levels. It detects and identifies critical points in the structure and allows us to optimize stress distribution in the structure. Stress can also be examined in the event of plastic deformations, or even until a crack occurs.

Photoelasticity can be divided according to various criteria. In terms of how the beam passes through the optically sensitive layer, it is possible to distinguish between transmission photoleasticity for transmitted light and reflective photoelasticity, usually identified as PhotoStress, either for vertically or obliquely reflected light. According to the criterion of locating the measuring point, photoelasticity can be planar for measurement at any point of the planar model or in the coating on the surface of the spatial model, and spatial for measurement at any point of the spatial model.

Unlike transmission photoelasticity, in which the experimental object can only be a model, completely made of optically sensitive material, in case of PhotoStress, the experimental object does not have to be only a model, but also a real object or a structural element with applied optically sensitive and reflective layer (coating). The PhotoStress method also makes it possible to identify and measure surface and residual stresses. The methods of photoelasticity require appropriately selected and consistently implemented means, methods and processes for coating, calibration, compensation, correction, separation, etc.

OEMs based on photoelasticity have already experienced significant development in former Czechoslovakia. This is also evidenced by the transmission polariscope FMB 53 (Fig. 2), a product of former Meopta plants, Bratislava, Elektropodnik Praha and the Research Institute TOZ Čelákovice from the beginning of the 1950s. At that time, it was a unique technical experimental facility, which won a gold medal at the EXPO World Exhibition 1958 in Brussels, Belgium.



(a) Polariscope FMB 53 when viewed from the side and in partial section.

(b) Overlap of two Moiré rasters: Original (undeformed) α and new (deformed) β.

Fig. 2: Polariscope FMB 53 in the TU laboratory in Košice.

Fig. 3 shows isochromatic fields created by the illumination of an object with white light by a reflective polariscope with linear polarization. The images were created during the development and verification of the methodology and the creation of an experimental measuring chain for the determination of simulated residual stresses by PhotoStress. At the same time, relevant procedures were applied in accordance with the methodology according to ASTM E 837-13a, both by blind cylindrical drilling and the Ring-Core groove method.

With a special arrangement or configuration, it is also possible to perform measurements to a limited extent during movement or dynamic measurements, e.g. within the analysis of cyclic stress of rotating parts. In such cases, it is necessary to place a sensor on the measured component, providing impulses for switching on the stroboscopic lamp, which serves as a light source. Using the stroboscopic effect, it is then possible to observe a time-stable image. Special methodologies for the analysis of various non-periodic dynamic effects in the form of various loading pulses, shocks, etc. are also developed [8].

Fig. 4 and Fig. 5 show isochromatic fields created by the illumination of an object with white light by a reflective polariscope with linear polarization. The images were created during the development and verifi-

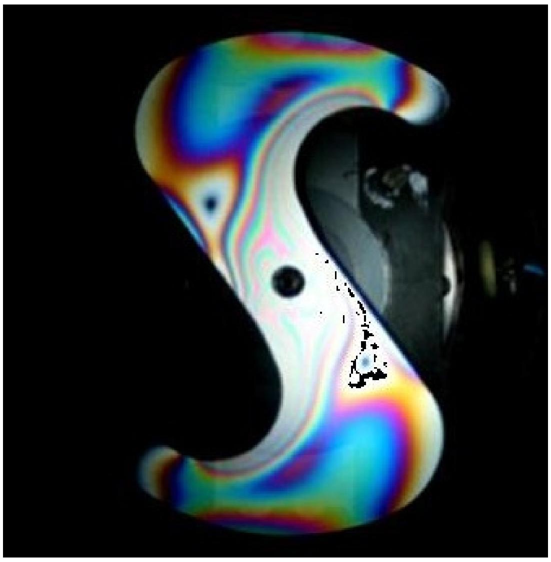
(a) Field of isochromatics around a blind cylindrical hole with a depth of 0.3 mm.

(b) Field of isochromatics around a groove with a depth of 2.0 mm for the Ring-Core method.

Fig. 3: The field of isochromatics around the blind hole or around the groove when illuminated with white light by a reflective polariscope with linear polarization in the analysis of residual stresses by PhotoStress.

cation of the methodology and the creation of an experimental measuring chain for the dynamic analysis by PhotoStress. Two samples of different shapes and a constant thickness were used, which were subjected to rotational analyzes at different angular velocities. The first test specimen had the shape of a modified S with two axes of antisymmetry (Fig. 4). The second test specimen had the shape of a disk with holes with four axes of symmetry (Fig. 5).

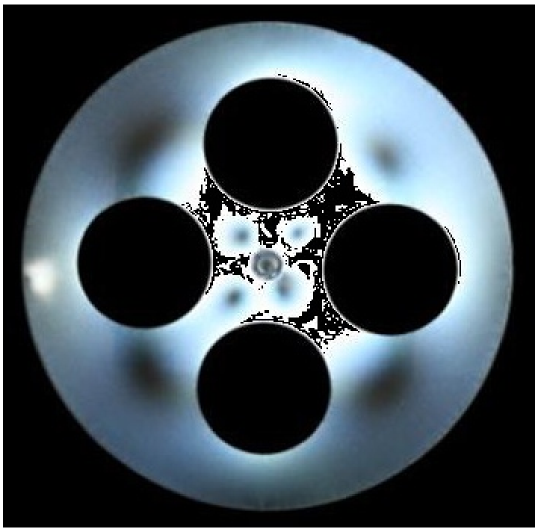
(a) Field of isochromatics at angular velocity ω = 125.7 rad·s^{-1}.



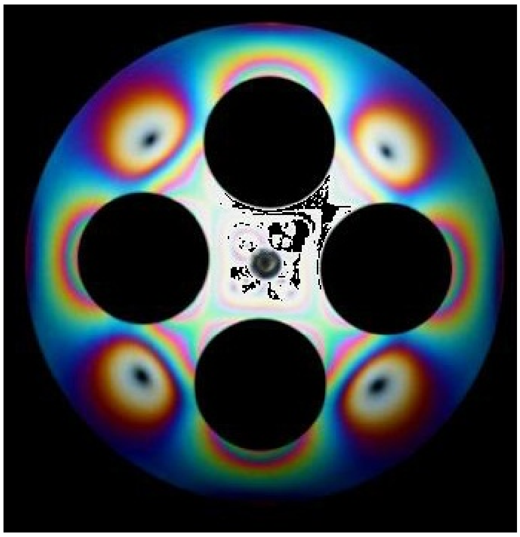
(b) Field of isochromatics at angular velocity ω = 712.1 rad·s^{-1}.

Fig. 4: Field of isochromatics when illuminated with white light by a reflective polariscope with linear polarization on a sample of S-shape of constant thickness as it rotates at a certain constant angular velocity.

The main technical and software tools used were reflective polariscope Vishay LF/Z-2, and in the case of dynamic analyzes, the stroboscopic white light source Strobex Model 135M-11, digital tachometer Laser Tacho, electric motor HSM 60, signal generator and digital camera. LF/Z-2 polariscope also included a digital compensator model 832 and software PSCalc^{TM}, preferably designed to obtain values of principal strains and principal normal stresses. The experimentally measured objects were made of a photoelastic film Vishay PS-1A with a reflective layer, with mechanical characteristics h = 3.05 mm, E = 2.5 GPa, μ = 0.38 and with an optical characteristic – sensitivity K = 0.15.



(a) Field of isochromatics at angular velocity ω = 230.4 rad·s^{-1}.



(b) Field of isochromatics at angular velocity ω = 816.8 rad·s^{-1}.

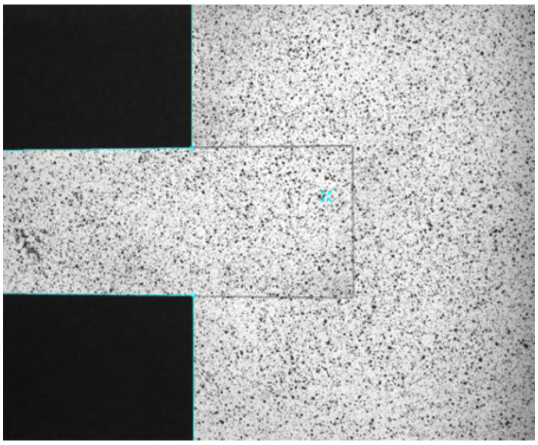
Fig. 5: Field of isochromatics when illuminated with white light by a reflective polariscope with linear polarization on a sample of a disc of constant thickness with holes as it rotates at a certain constant angular velocity.

3.3 Digital image correlation method

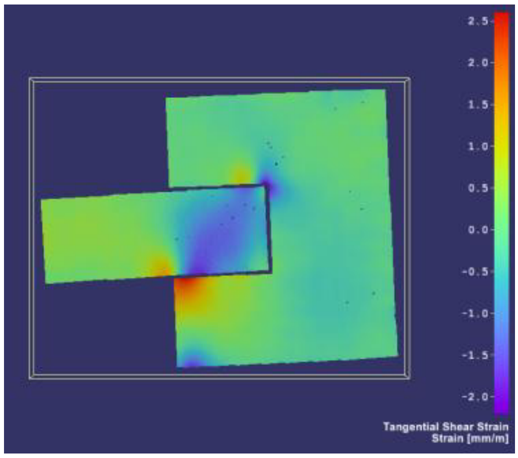
Current modern so-called "basic" OEMs which are preferably dedicated for displacement analysis include the digital image correlation (DIC) method. DIC correlates images of a stochastic pattern created on the surface of the examined object in the process of its loading and thus also stressing. The total deformation of the object's surface is given by a set of deformations of individual image elements – facets. Therefore, the accuracy of the DIC is based on the displacement analysis algorithm used. The comparative process consists in finding the extremes of the correlation functions of the corresponding facets. Basic applied correlation algorithms include the translational tracking algorithm and the method of included surfaces. The first of the algorithms does not consider the deformation of the facets but only their displacement. The second requires knowledge of the correlation coefficients of the pixels inside the 3×3 facets. The Newton-Raphson algorithm, in turn, works with a minimum of correlation function. The algorithm based on optical flow is used to analyze displacements with subpixel accuracy. At present, the correlation algorithm using pseudo-affinity transformation is relatively widespread. Correlation errors of a statistical or systematic nature can affect the accuracy of measurements. For 2D observation and measurement, one camera is used, placed perpendicular to the measured sample or the object. For observation and measurement in the 3D image correlation mode, two cameras are used, which capture the observed area from different directions [9].

An example of the application of the DIC method is the analysis of deformations within a contact task. It was modeled on a bracket, tightly inserted into a rectangular groove on one side and stressed by bending on one side. Fig. 6a shows an experimental object with a stochastic pattern applied to the surface. Fig. 6b shows the obtained field of bevel sizes (shear deformation) γ. Fig. 7 then depicts obtained field of vectors – magnitudes and directions of principal strains ε_1 and ε_2.

The main technical and software tools used were Dantec Dynamics Q-400 optical system, as one of a series of Q-400, Q-400 Micro, Q-450 and Q-480 systems, and the Istra4D software. The Q-400 system typically consists of two cameras with CCD sensors, and up to eight cameras can be used in the extended mode. The illumination is usually realized by a halogen reflector with white light or a HILIS LED illuminator with homogeneous cold light. Istra4D software performs all processes related to measuring, processing and evaluating results. Since the analysis by the DIC method was preceded by the analysis by the PhotoStress method, the experimentally measured objects on which the stochastic sample was sprayed were also preserved. The material was therefore a photoelastic film PS-1A from Vishay with mechanical characteristics h = 3.05 mm, E = 2.5 GPa, μ = 0.38.

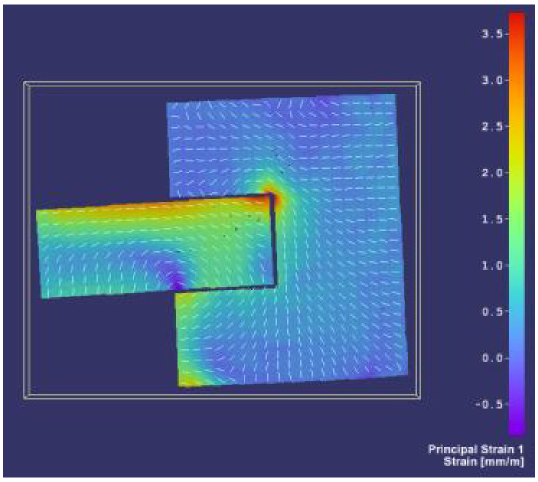


(a) Stochastic sample.

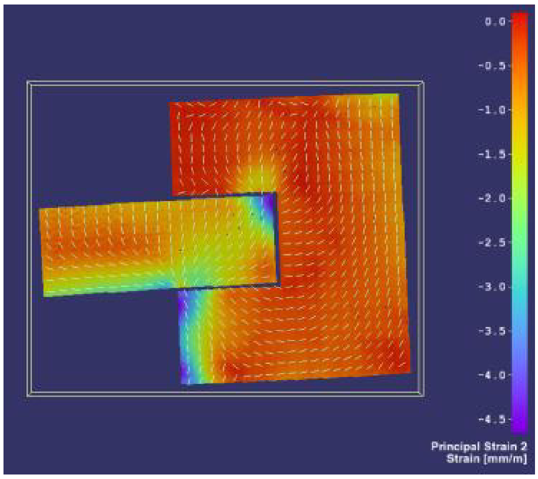


(b) Bevel size filed γ $[10^{-3}]$.

Fig. 6: Stochastic sample and field of bevel sizes (shear deformation) γ in the analysis of deformations within a contact task by the DIC method.



(a) Stochastic sample.



(b) Bevel size filed γ $[10^{-3}]$.

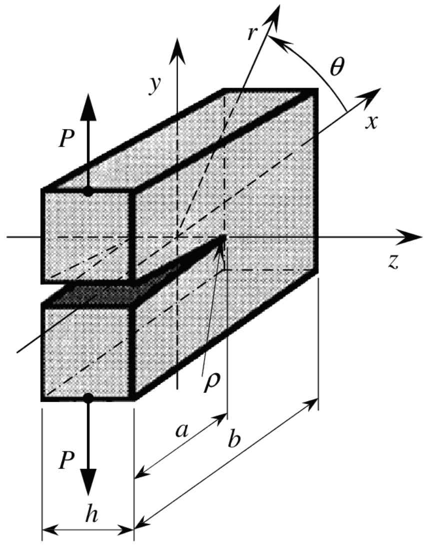
Fig. 7: Field of vectors – magnitudes and directions of principal strains ε_1 and ε_2 during the analysis of deformations within the contact task by the DIC method.

3.4 Holographic interferometry method

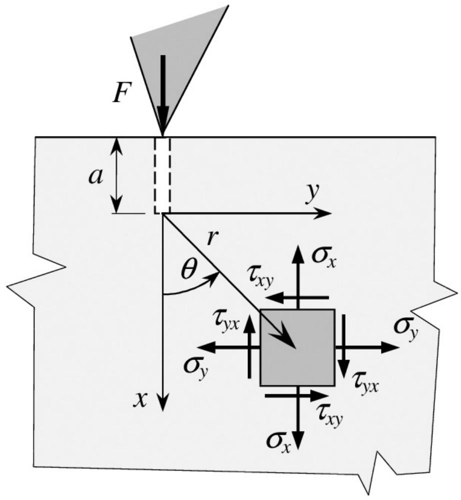
Other modern OEMs are methods based on the holographic principle. They are based on the creation of three-dimensional images - holograms, e.g. Fresnel, image, Frauhofer or Fourier. Their creation is based on capturing an object using coherent light and waves reflected from the object. It includes e.g. holographic interferometry (HI). Here, during reconstruction of the hologram, the information wave or the wave in question is reconstructed. If the reconstruction wave is an exact copy of the reference wave, the information wave with the same amplitude and phase is restored. If the examined object is removed during the reconstruction, it is possible to see its image in exactly the same place and in the same shape as it took when creating the hologram. If the object under investigation is not removed during the reconstruction, then there are two waves behind the hologram. The first comes from the reconstructed hologram, the second is spreading from the object. These are coherent waves that interfere with each other. The created interference pattern, the so-called holographic interferogram, will capture those changes in the object that occurred between the creation of the hologram and its reconstruction. If the position, dimensions or shape of the object change during the reconstruction, the interference pattern also changes. This is HI in real time. In the second variant HI, two or more subject waves corresponding to different states of the same object are gradually registered in one recording environment. During the reconstruction of the hologram, the recovered waves interfere with each other and form interference patterns. This is therefore a method of two or more exposures [9, 10].

HI is a typical two-step process in which information in the form of an observable macroscopic image can be obtained by reconstructing a record in which information characterizing at least one physical state of the object under investigation is encoded.

The following is an example of applying the HI method to a newly developed methodology for the analysis of deformations and stresses around the crack front (root, tip). At the same time, it is a matter of obtaining data for experimental determination of the coefficient or stress intensity factor K_I, or K_{II} or K_{III} for Modes I or II or III of crack opening and material separation. Fig. 8a shows a Mode I model of material separation and Fig. 8b shows a preparation for describing stress around the crack front (root, tip) in both Cartesian and polar coordinate systems.



(a) Crack opening and material separation for Mode I.



(b) Rectangular planar element for stress analysis around the crack front (root, tip) in both Cartesian and polar coordinate systems..

Fig. 8: Crack opening model and rectangular planar element around the crack front (root, tip) for stress and strain analysis by HI method.

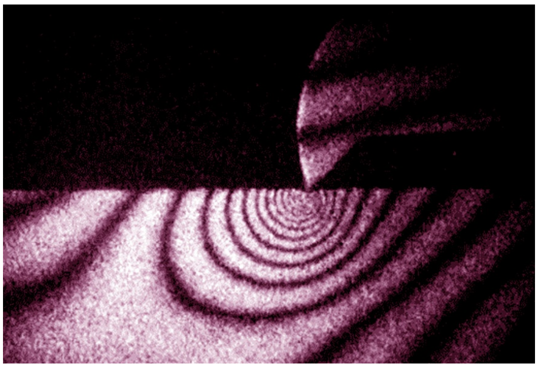
Fig. 9a shows an image of a holographic interferogram from the vicinity of mutual force interaction of two objects according to Fig. 8b. For a better identification of individual isopachs, the real image in Fig. 9a has a slightly adjusted color density. Experimentally investigated were various situations of force applied to an object without a crack and with a defined crack or notch. Fig. 9b depicts a field visualization of discrete isopachs 1 to 8 obtained from the holographic interferogram in Fig. 9a in the angular range 0° to 180° from the vicinity of the examined point for a certain parameter (polar coordinate) r.

Fig. 10 shows angular dependences of the normal stress σ_y and the shear stress τ_{xy} around the crack face (root, tip) for a certain parameter r, obtained by the HI method. With the help of these data and the use of appropriate analytical relations of fracture mechanics for stress analyzes from the crack environment, it is then possible to express the coefficient or stress intensity factor K_M for the respective Mode M and for the respective stress or load condition of a certain material.

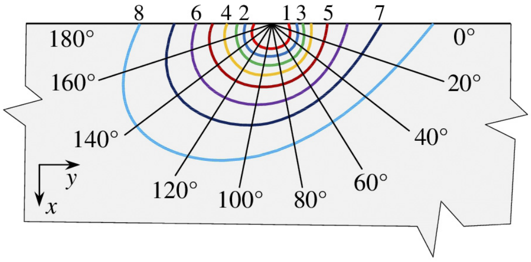
The main technical means used was a coherent radiation source with a helium-neon laser with a radiation wavelength of 632.8 nm and a CCD camera. Other elements of the optical system used were continuous optical laser beam splitters, lenses and a holographic plate. The experimental measured object was made of natural styrene-butadiene rubber with mechanical characteristics E = 4.24 MPa, R_e = 0.77 MPa and R_m = 3.01 MPa.

3.5 Digital speckle interferometry

The approach characterized in the previous paragraph makes it possible to organically incorporate the method of interference of laser spots, i.e. Speckle interferometry (SPI), into the uniform classification of interference techniques. The correlation SPI method is based on the coherent superposition of speckle fields formed by a light wave reflected from the optically rough surface of the examined object and a reference wave. The presence of a reference wave during the recording of a speckle image induces an intensity distribution in the imaginary plane of the optical system depending on the relative phase shift of the interfering speckle fields. Deformation of the object's surface will cause a change in the intensity distribution in the resulting speckle

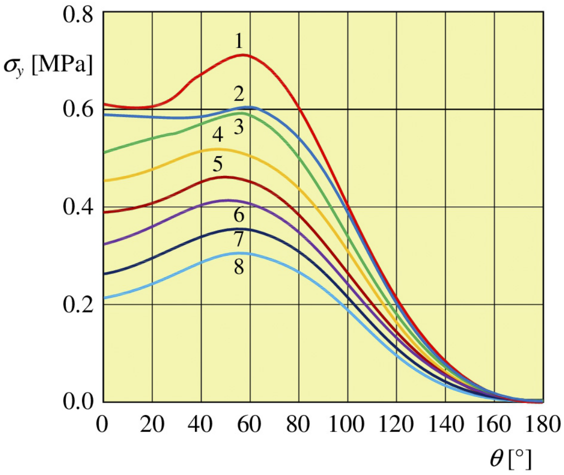


(a) Real image of holographic interferogram from the environment of mutual force interaction of two objects.

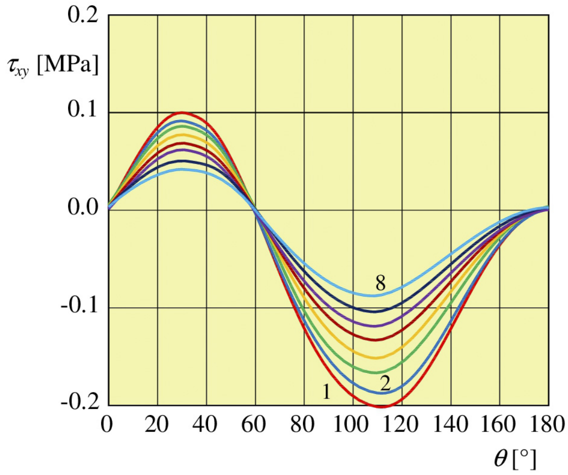


(b) Visualization of the field of discrete isopachs 1 to 8 of the holographic interferogram in the range of 0° to 180° from the vicinity of the examined point.

Fig. 9: Holographic interferogram and corresponding isopachs obtained for stress and strain analysis around the crack front (root, tip) by the HI method.



(a) Stress angular dependence σ_y.



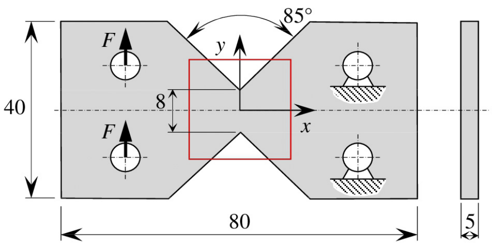
(b) Stress angular dependence τ_{xy}.

Fig. 10: Stress angular dependence σ_y and τ_{xy} around the crack front (root, tip) in distance r gained by the HI method.

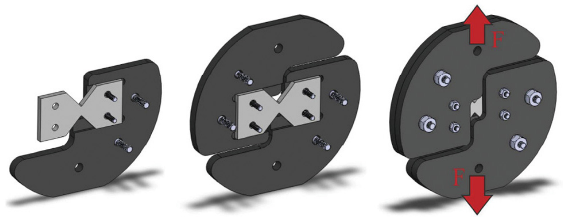
image in this case. The phase-shifting SPI method, in turn, consists of double-recording two images of an object, one of which is slightly shifted relative to the other. An improved method of SPI is the Electronic Speckle Patten Interferometry (ESPI), also known as digital SPI (DSPI) or TV holography, using a camera with a CCD or CMOS sensor as a recording device. The speckle image recorded by the digital camera can be considered a hologram, but instead of reconstructing it, the speckle images are correlated. Paradoxically, the speckle effect is considered an undesirable phenomenon in traditional HI that needs to be eliminated or at least appropriately suppressed. ESPI measurements can be performed either in-plane or out-of-plane. The superposition of the reference light and the light reflected from the surface of the object creates a new speckle image – the interferogram [2,11]. Overall, the possibilities of using SPI and ESPI are essentially identical to the areas of application of HI, while ESPI is used mainly to measure very small displacements and relative deformations.

The following is an example of the application of the ESPI method to a newly developed methodology for the analysis of deformations and stresses in place of stress concentrators on structural elements. Fig. 11 shows a design of the shape and the method of specimen loading by shear stress for the purposes of stress and strain analysis by the ESPI method. Fig. 12 then shows the resulting stress distribution field σ_3 and τ_{xy} in the test specimen under its shear stress obtained by the ESPI method.

The main technical and software tools used were the white spray Diffu-Therm, optical system Q-100 from Dantec Dynamics as one of a series of Q-100, Q-300, Q-500 and Q-600 systems, and the Istra software. The Q-100 system has a miniaturized 3D ESPI sensor that uses four different illuminating directions and one central CCD camera, so it has up to four sensitivity vectors. The Istra software then ensures all processes of measuring, processing and evaluating the results. Stainless steel sheet with mechanical characteristics $R_{p0.2}$ = 300 MPa, R_m = 658 MPa and A_{80} = 63.3% was used as the material of the test experimental sample.

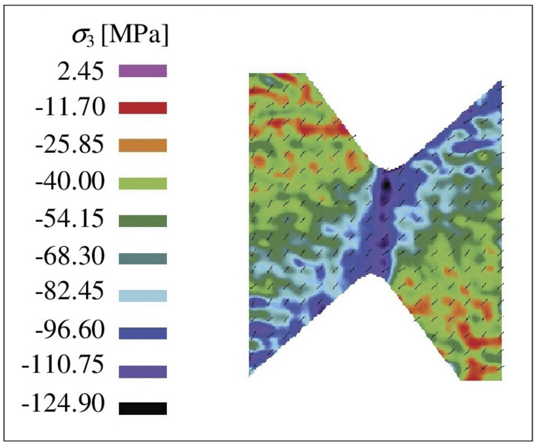


(a) Test sample with a sharp V-notch with an opening angle of 85 ° – the so-called butterfly shape.

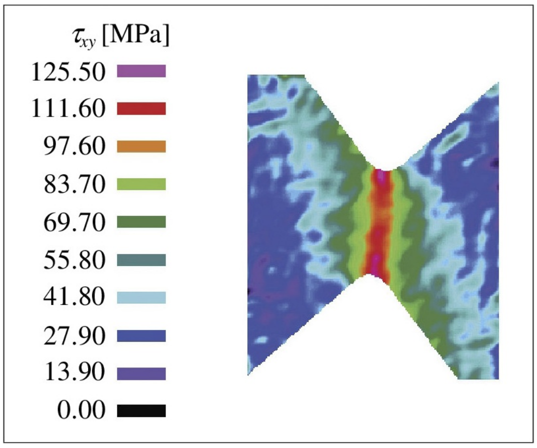


(b) Load and clamping jig (frame).

Fig. 11: Design of the shape and the method of specimen loading by shear stress for the purposes of stress and strain analysis by the ESPI method.



(a) Field of distribution of principal normal stresses σ_3 [MPa].



(b) Field of distribution of shear stresses τ_{xy} [MPa].

Fig. 12: Field of distribution of stresses σ_3 and τ_{xy} inside the test specimen during shear loading, obtained by the ESPI method.

3.6 Digital speckle shearography

Another relatively new and specific OEM method is Digital Speckle Shearography (DSSG). It uses a coherent laser light and speckle effect to measure deformation, but unlike holographic methods, it is only able to record a deformation gradient. Compared to SPI, however, it is more resistant to disturbing environmental influences, e.g. shocks, but, at the same time, its sensitivity is extremely high. The essence of the measurement lies in the comparison of the reference state of the surface of the object with the state of the surface when it is deformed by mechanical or thermal load. Then the interferograms captured before and after deformation are superimposed. The result is a stripe pattern, the so-called shearogram, corresponding to the deformation gradient on the surface. The method is applicable to a wide range of materials from steel, ceramics to plastics and composites, in which it relatively successfully identifies various defects, discontinuities, anomalies, delaminations, cracks, etc. A typical representative of measuring devices for the DSSG method is the optical system Q-800 of the Q-800 and Q-810 series from Dantec Dynamics with the appropriate software [7]. This system is based on a shearographic sensor with an integrated high-resolution CCD camera.

4 Origin of presented application examples

All of the mentioned OEM application examples or their key stages were realized using technical and software means, i.e. HS and SW equipment exclusively of the experimental workplace of the Department of

Applied Mechanics and Mechanical Engineering, Faculty of Mechanical Engineering, Technical University in Košice. They formed part of practical tasks or research programs for the development of new experimental methods for the analysis of material properties and the analysis of the response of structural elements or entire structures to loading, as well as the assessment of limit states [12–14].

In cases where the nature of the problem allowed, the results obtained by OEM methods were verified by other experimental methods, most often by tensometry or non-experimental, i.e. analytical or numerical methods, always with comparable results.

5 Conclusion

In this paper, individual OEMs were briefly presented in approximately chronological order of their origin, development and application. Although their development is rapid, their current state, technical and software resources, or even the principle does not yet allow their deployment for instance in the area of measurement of dynamic events, especially the measurement of stochastic character and, at the same time, under difficult conditions of negative influences, e.g. as a replacement for dynamic strain gauges. Their use is therefore limited mainly to laboratory conditions.

However, OEMs find their specific application as sophisticated non-contact methods mainly in the development of new methods for determining deformations, stresses and material characteristics, mainly in the field of fracture mechanics, residual stresses, elemental analysis in the field of elastic-plastic deformations, limit state analysis, etc.

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