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The application of holographic interferometry to the analysis of composite materials structure*

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The holographic real-time method is adapted for the purpose of the quantitative investigation of the displacement vectors on the boundaries of components of composite materials. The measurements in the vicinity of boundaries are carried out with the assumption that the position of the zero-order fringe is not known, while the succession of fringe orders is determinable. Some results obtained by this method are presented.

Problems of holographic interferometry of composite materials

The extent of application of composite materials in various branches of industry is continuously increasing, since a suitable selection of the quantities, shapes and properties of the individual components can result in the achievement of the desired characteristics of the composite material.

The experiments described in this paper were aimed at the measurement of displacement vectors of general directions in the vicinity of the mechanical boundaries, on the front walls of the specimens of resin concrete. The resin concrete is a typical representative of the composite materials having a macromolecular matrix with a dispersed mineral phase. The specimens were clamped in a rigid frame, supported along the whole area of their base and loaded with a vertical concentrated load $\vec{P}$. This load was controlled with a dynamometer, as shown in figs. 1a, b and 2.

The holographic interferograms obtained have shown a rapid change of the direction, frequency and localization of fringes in the vicinity of interphase boundaries. The whole structure of the interference pattern was as complex and irregular as to eliminate entirely an a priori determination of the zero order fringe position. Moreover, except for the investigated deformation displacement vector $\vec{u}$, while loading the specimen a strong rigid-body motion was involved. This unwanted motion is due to the screw-system loading device and rather high load $\vec{P}$ (from 10^3 to 10^4 N) acting on the area of 100 mm^2.

In the interferogram the rigid-body motion caused an equidistant fringe system, which — added the deformation fringes and not compensated — would completely wash away the phenomena observed.

The interferogram characteristics mentioned above had a decisive influence on the choice of the evaluation method and the suitable experimental arrangement.

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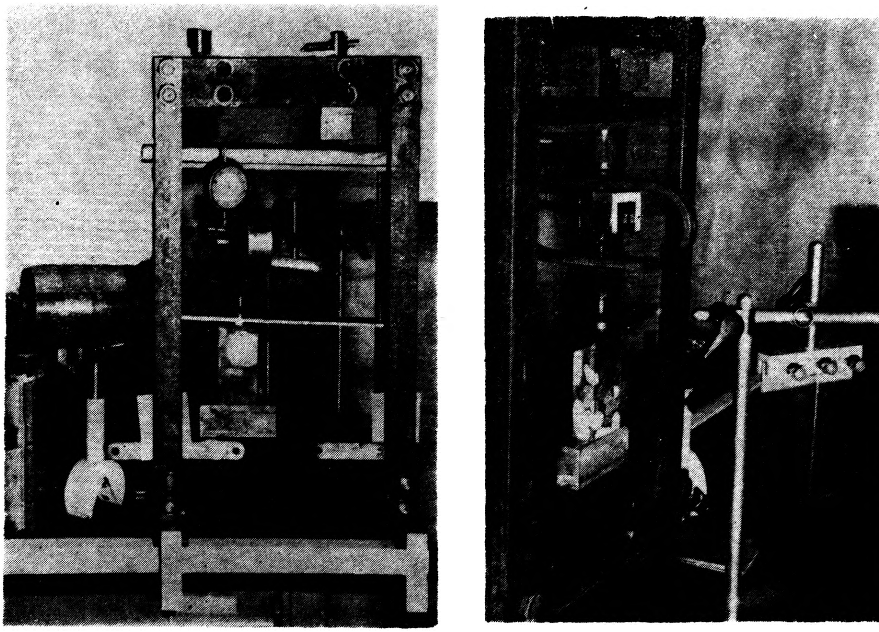

Fig. 1. Photo of the arrangement: a. Photo of the back side of the loading frame with a specimen and a dynamometer. b. The hanging hologram, developed "in situ"

Method of evaluation

The position of the zero-order fringe being not known, the Bonch-Bruievich's method could not been used in its original form [1]:

$$\vec{u}(\vec{r}_{i1}-\vec{r}_0) = \lambda n_{i1}, \quad \vec{u}(\vec{r}_{i2}-\vec{r}_0) = \lambda n_{i2}, \quad \vec{u}(\vec{r}_{i3}-\vec{r}_0) = \lambda n_{i3}, \tag{1}$$

where $\bar{u}$ is the deformation displacement vector (shortly, displacement vector), $\vec{r}_{ik}$ are vectors describing the viewing directions related to the point A_i, $\vec{r}_0$ belongs to the direction of illumination plane wave, λ is the wavelength used, and n_{ik} are the corresponding fringe orders.

The modified form, suggested for instance by Kozachok [2], was more appropriate

$$\begin{aligned} \vec{u}(\vec{r}_{i2}-\vec{r}_{i1}) &= \pm\lambda(n_{i2}-n_{i1}), \\ \vec{u}(\vec{r}_{i3}-\vec{r}_{i2}) &= \pm\lambda(n_{i3}-n_{i2}), \\ \vec{u}(\vec{r}_{i1}-\vec{r}_3) &= \pm\lambda(n_{i1}-n_{i3}). \end{aligned} \tag{2}$$

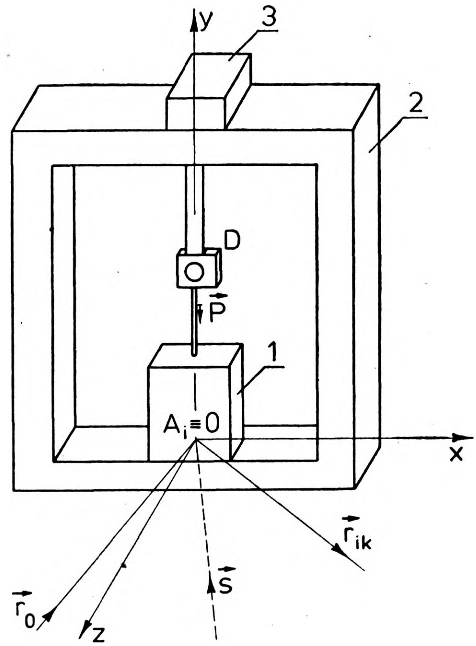

Fig. 2. Scheme of the clamping and loading of the specimen, including the directions of illumination, viewed in the i-th system of coordinates originating at the point A_i of the front wall. $\vec{P}$ — concentrated vertical load, $\vec{r_0}$ — illumination direction, $\vec{r_{ik}}$ — k-th viewing direction of the point A_i ($i = 1, 2, ..., n$; $k = 1, 2, 3$), D — dynamometer, x, y, z — coordinate axes, $\vec{s}$ — sensitivity vector (1 — specimen, 2 — rigid frame, 3 — screw system)

All the vectors presented in (2) are described in the Cartesian system of coordinates, the origin of which coincides with the point A_i under investigation, and the directions of x, y, z axes are obvious from fig. 2. Then each vector can be projected onto these coordinate axes by means of direction cosines so as to express its Cartesian components. Using these direction cosines the system of equations (2) may be expressed in the matrix form:

$$[R]\cdot[U] = [N]. \tag{3}$$

(It should be noticed that during the measurement, while passing from A_i to another point A_{i+1}, and so on, the origin of the system of coordinates is also translated into these points.)

We have

$$[R] = \begin{bmatrix} \cos\alpha_{i2}-\cos\alpha_{i1} & \cos\beta_{i2}-\cos\beta_{i1} & \cos\gamma_{i2}-\cos\gamma_{i1} \\ \cos\alpha_{i3}-\cos\alpha_{i2} & \cos\beta_{i3}-\cos\beta_{i2} & \cos\gamma_{i3}-\cos\gamma_{i2} \\ \cos\alpha_{i1}-\cos\alpha_{i3} & \cos\beta_{i1}-\cos\beta_{i3} & \cos\gamma_{i1}-\cos\gamma_{i3} \end{bmatrix}. \tag{4}$$

$$[\mathrm{U}] = \begin{bmatrix} u_x \\ u_y \\ u_z \end{bmatrix}, \qquad (5)$$

$$[N] = \begin{bmatrix} \pm(n_{i2}-n_{i1}) \\ \pm(n_{i3}-n_{i2}) \\ \pm(n_{i1}-n_{i3}) \end{bmatrix}. \qquad (6)$$

In order to obtain the components u_x, u_y, u_z of the displacement vector $\vec{u}$, we require additional information, because the system of equations (3) has not a single solution. This additional information is the fringe order succession, which determines the signes of the fringe order differences in (3). Thus the ambiguity is avoided.

All the necessary calculations being routine ones and commonly used, have not been mentioned in this paper.

The experimental arrangement

It is well-known that in holographic interferometry only such displacement vector $\vec{u}$ is registered, whose projection onto the sensitivity vector $\vec{s}$ has a non-zero value. The sensitivity vector, sometimes called the viewing symmetral [3], halves the angle between the vectors of illumination $\vec{r}_0$ and viewing $\vec{r}_k$ directions.

In the measurements carried out with the resin concrete specimens, it has been expected that the displacement vector $\vec{u}$ has a general direction, which implies that all three Cartesian coordinate components of $\vec{u}$ must be registrable with the holographic setup used.

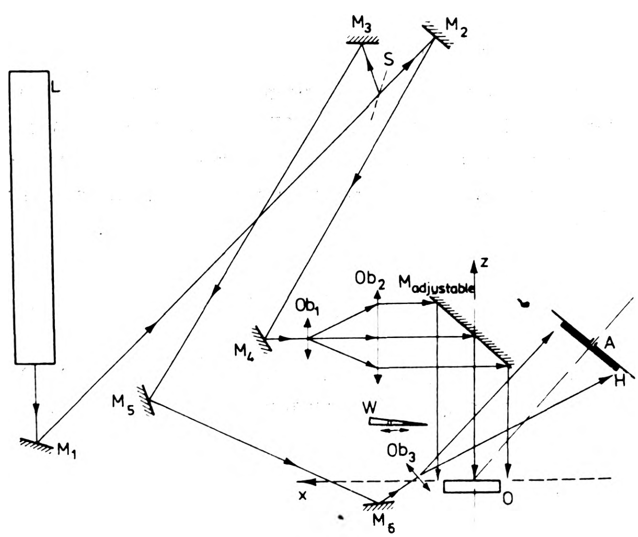

Fig. 3. Scheme of the experimental arrangement: *M* — mirrors, *O* — object, *Ob* — objectives, *H* — hologram, *A* — viewing aperture, *W* — optical wedge

Taking into account all the requirements stated in previous text, the setup in fig. 3 must inherit the following features:

a. The sensitivity vector must not lay in any of coordinate planes — (xy), (yz), (zx).

b. The compensation of the unwanted rigid body motion, which occurs in the form described in fig. 4, must be possible.

c. It must be a possibility to determine the fringe order succession.

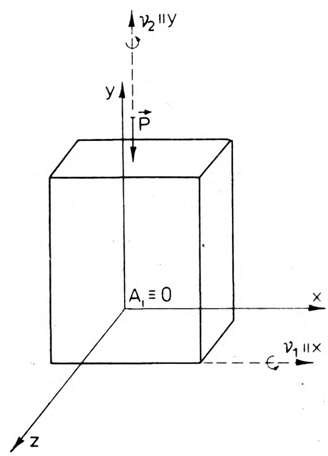

Fig. 4. The additional rigid-body motion which may occur during the specimen loading and must be compensated being added to the deformation displacement vector (specimen under load is rotated as a rigid-body round the axes ν_1, ν_2)

The required sensitivity was achieved by means of the geometry of the holographic setup. The front wall of the specimen lay in the (xy) plane, which included the origins of the coordinate systems in points A_i. The illuminating direction was constant for all measurements and lay in the (xz) plane, while the viewing directions $\vec{r}_{ik}$, determined by the aperture A position, were chosen so that the sensitivity vector $\vec{s}$ always satisfied the requirement a.

Because of b. and c. requirements the real-time arrangement was inevitable. The last element adjusting the object in the object beam optical system, was a large adjustable mirror. Its slight movement compensated well the rigid-body motion fringes.

After compensating these undesirable fringes a movable optical wedge was inserted into the object beam. The plane of the wedge was perpendicular to the direction of light propagation. Translations of the wedge across the field of view made the fringes travel, and from the known phase differences caused by the wedge and from the corresponding movement of fringes the fringe order succession was determined.

Experimental results

Solutions of the system of equations (3), for discrete points A_i along the trajectory which intersected the mechanical boundary in the (xy) plane, were approximated to give three smooth curves, each for the component of the displacement vector

u_x, u_y, u_z, respectively. This information was sufficient for further processing, typical in the strain analysis.

All the measurements were carried out under the assumptions that the load $\vec{P}$ did not cause cracks either in matrix, or in the mineral phase, and that on the boundary the strain satisfied equations of compatibility. Since the matrix was supposed to inherit also time-dependent mechanical features, two series of measurements were done: the first immediately after the load application ($\Delta t = 0$), the second after $\Delta t = 48$ hour time delay.

Conclusions

As can be seen from fig. 5, the influence of the mechanical boundary on the displacement vector was quite significant. It can be explained as follows: In the vicinity of the boundary the gradient of the displacement vector was so high, that the frequency of fringes exceeded the resolution limit. Therefore, in a narrow region between two

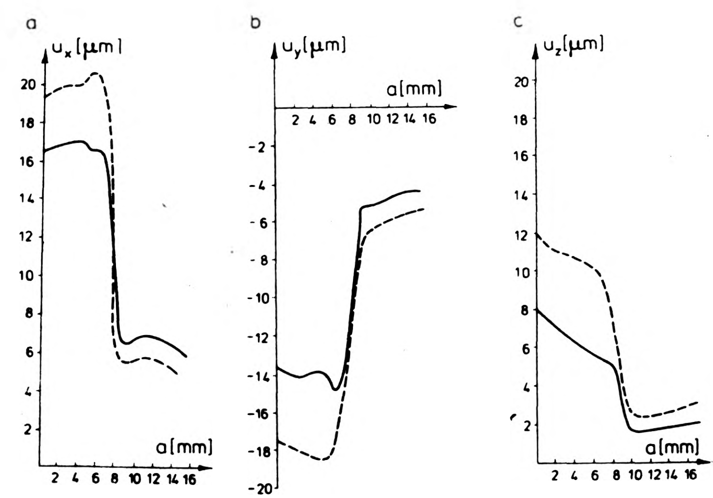

Fig. 5. Results of measurements — curves of the displacement vector components $u_x(a)$, $u_y(b)$, $u_z(c)$ along the trajectory intersecting the mechanical boundary; initial load $P_0 = 5000$ N, additional load 1000 N, ——— $\Delta t = 0$ hours, – – – – $\Delta t = 48$ hours

following resolved fringes lying on the opposite sides of the boundary, there was a number of accumulated and unresolved fringes. The u_x, u_y, u_z components of the displacement vector before and after the trajectory crossed the unresolved gray region along the boundary being known from eq. (3), the fringe order step Δn can be determined. Its existence was evident from the shape of curves in fig. 5. As the condition of compatibility held, it was possible to approximate the curves even for the intersection with the boundary.

References

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Применение голографического интерферометра для анализа сложной структуры материала

Метод голографии в истинное время был адаптирован для количественных испытаний векторов перемещения на границах компонентов сложных материалов. Измерения произведены в соседстве границ при допущении, что положение полосок нулевого порядка является неизвестным, но можно определить очерёдность интерференционных рядов. Приведены некоторые результаты, полученные этим методом.