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The Methodology of Application of Optically Sensitive Coatings in the Photoelastic Tests of Medical Models

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KEY WORDS
Photoelastic coating method, medical model, cranial syndesmosis.

ABSTRACT
The article describes the methodology of applying optically sensitive coatings on medical models, e.g. the models of the upper skull and cranial syndesmosis. The article also lists all of the most important problems that may occur during this process and the methods of solving them. Also, the new approach towards applying optically sensitive coating on the cranial syndesmosis models is introduced. The correct application of the coating is one of the most important issues of the photoelastic research, as it leads to the proper determination of the stress distribution in complex elements of medical models, such as models of the upper part of human skull.

1. Introduction

The numerical analysis based on discreet models in most cases needs experimental verification. It especially important in case of constructions and the load-carrying structures distinguished with a high level of geometrical complexity [1,2,3].

The experimental research can be done on real objects or their models. The latter are used mainly in cases where the stress distribution needs to be tested in those object areas that are difficult to access or the inner areas of structures.

The photoelastic method can be used to verify the stress distribution in spatial models. Photoelasticity is based on the temporary double refraction effect. This effect occurs in some transparent materials under load. Two photoelastic methods are commonly used: the photoelasticity method of stress freezing and the optically sensitive layer method [4,5,6].

The latter method requires applying an optically sensitive coating with the right photoelastic koeficients so the appropriate resin needs to be chosen. The application technique depends on the type of a tested model. Usually in case of medical models, e.g. the cranial syndesmosis model, a special approach is needed. A serious analysis has to be performed in order to determine which of the coating application methods gives the most realistic model mirroring a real-life object.

2. Material and Methods

Photoelasticity – optically sensitive layer method

The method is based on the phenomenon of birefringence [7]. The birefringence phenomenon occurs when a ray of light passing through a birefringent material experiences two refractive indices. On leaving the material, they experience a phase retardation originating in the various speeds of the rays in the area of the birefringence. The phase retardation is proportional to the principal stresses difference.

The reflected light method allows for the surface stress distribution analysis of the model based on the isochromatics lines distribution. Isochromatics are the geometric locus of the fixed points of the principal stresses difference; therefore they can be used to determine the maximum shear stress distribution.

The Reflection Polariscope (Vishay Micro-Measurements, Raleigh, NC) was used to carry the experiment (Fig.1). The Reflection Polariscope consists of the white light source, special polariscope and analyzer filters and quarter-wave plates.

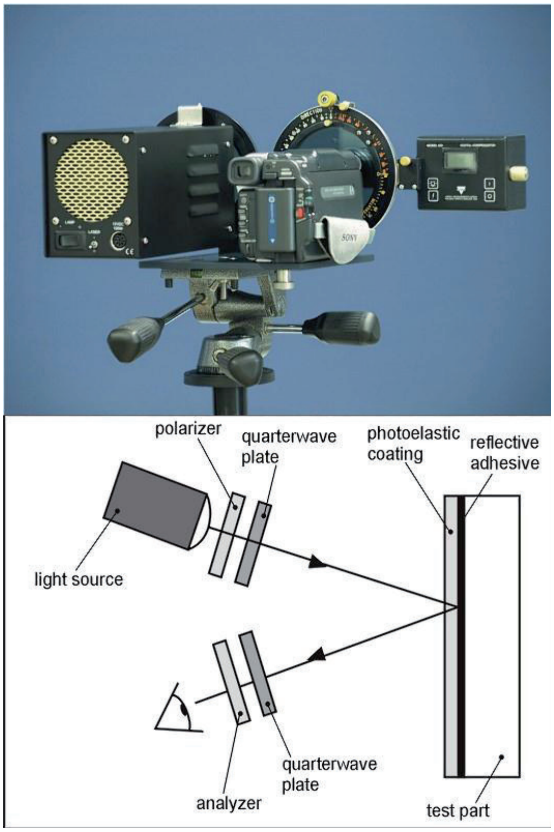

Fig. 1: *Vishay Reflection Polariscope and the schematic representation of the polariscope model analysis.*

The polarized light is incident on the photoelastic coating applied on the tested model under load, then it reflects from the reflective adhesive, goes back through the photoelastic coating and separates into two component rays, and their planes of vibration coincide with the principal stress directions, and their mutual retardation is proportional to the difference in the principal strains of the model. Then the light passes through the analyzer, and the isochromatics lines distribution can be observed on the surface of the tested model.

The quarterwave plates are used to achieve the circular polarization, and in such a setup only isochromatics lines are visible, without isoclinics (isoclinics are the locus of the points in the specimen along which the principal stresses are in the same direction), thus rendering a clearer image.

It is very important to prepare and apply the optically sensitive coating in the right way. The materials used for producing photoelastic and optically sensitive coatings should meet several requirements:

- *transparency, optical and mechanical homogeneity,*
- *high optical sensitivity,*
- *substantial linear dependence between the stresses and deformations, also between stresses and optical effects,*
- *lack of optical nor mechanical creep,*
- *proper castability before hardening.*

Vishay is also a manufacturer of quality optically sensitive materials, ranging from ready-made, factory-hardened semi-finished products to liquid resins that need to be prepared at a lab. The PL-1 PL-8 optically sensitive resins (and PCH-1 and PCH-8 curing agents) were used for our analysis. These epoxy resins are suitable for models not subjected to serious deformations (the maximum elongation does not exceed 5%, the Young's modulus is E=2900 MPa, and the Poisson ratio v=0,36). The PL8 epoxy resin is preferred for long-term testing as its prolonged darkening time does not allow for observing the isochromatics distribution lines.

The process of preparation and application of the coating is complicated and requires experience. First, the model should be analysed, as its shape and size determine the number of coating elements and the distribution of division lines between them. The upper skull models are of special concern because of the cranial syndesmosis complex structure. With its narrow and irregular shape it should be the prime determinant of the choice of the right thickness of the optically sensitive coating to properly model the cranial syndesmosis surface. After the series of tests, the t = 2mm thickness proved to be right. When a coating layer was too thick, it was not possible to adequately model the cranial area and the models were reduced to a simple skull with no cranial syndesmosis present. Also, coated with too thick a layer such models were too rigid. When we tested the models with the coating thickness less then t = 2mm, the photoelastic qualities were affected, since they depend of the thickness of the coating layer. Also, when the layer of coating was too thin, it proved to be very difficult to separate from the model because it would stick to the cranial syndesmosis area.

To achieve the most accurate analysis results and to cover the cranial syndesmosis area precisely with the t = 2mm coating, the 2:1 scale was chosen for the upper skull and 4:1 and 3:1 scale for the cranial syndesmosis area. After the series of tests, the 1:1 scale proved to be inadequate, as the shape of the cranial syndesmosis could not be precisely reproduced.

The teflon plate from Vishray Inc (Fig. 2) was used to produce the optically sensitive coating. The plate should be leveled and heated to 35°C so the resin can reach the partial polymerization stage. The amount of resin needed for an experiment depends on the thickness of the optically sensitive coating and the amount of the surface that needs to be covered with the resin (silicone frames should be used to mark the area limit). In most cases the maximum possible size (250x250mm) coating elements were created.

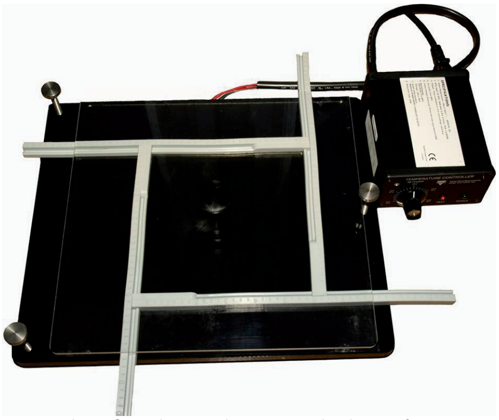

Fig. 2: *The teflon plate (Vishay Inc) with silicone frames.*

Prior to casting, the PL-1 resin and the PLH-1 hardener mixture has to be prepared. The ratio is 5:1. The total amount of mixture is determined by:

$$W = \rho . A . t [g] \qquad (1)$$

where: ρ = PL-1 resin density (g = 1.13x10^{-3} g/mm^3), A = area to be cast (the width x length of the surface framed with silicone strips [mm^2], t = desired thickness of the optically sensitive layer [mm]

When the mixture is prepared, care should be taken to avoid creating air bubbles, which could damage the coating and/or make observing the isochromatic lines distribution difficult. Should air bubbles appear, it is possible to off-gas the mixture in the vacuum casting machine UHG 400 in subatmospheric pressure of 2÷50 hPa. Mixing needs to be carried with a special temperature measuring instrument, to make sure the temperature reaches the manufacturer's recommendations (which, in case of the PL-1 resin, is 55°C) prior to casting. In order to remove the coating easily, a special sheet needs to be placed on the Teflon plate, and then the silicone frames. The frames should be coated with the mineral oil to seal the joints (and for easy removal after the casting). The resin hardening process takes several minute. Tests need to be carried to determine the exact amount of time needed for the partial polymerization. The time needed for the cast PL-1 sheet (width x length: 250x250mm, thickness: 2mm, the casting plate temperature: 34°C) to reach the partial polymerization stage is approximately 45 minutes. The resin is ready when the it does not stick to the probe, also the corner of the cast resin should easily separate from the cast sheet, and when deformed should go back to the initial state gradually. When those conditions occur, the resin is cast ready and can be applied to a model. It should be applied within 15 minutes, otherwise the polymerization process becomes too advanced and the resin is too rigid to form. The exact way of breaking the cast coating into elements should be planned beforehand, so the model can be covered with the partially polarized resin in time.

The edges of the cast-ready resin need to be trimmed because of the meniscus on the frames contact lines. Cutting can be performed with regular scissors. The scissors, the model and the gloves should be coated with the mineral oil, it makes contouring process smoother and also helps to prevent the coating deformation that might occur due to the surface friction. During the partial polymerization stage the resin coating is very plastic and can be applied even to very complex shape models. The applied cast resin should be left on the model for 24 hours, until it is fully polymerized.

In some cases it is necessary to cut the dry coating in order to remove it from the model. The hardened coating applied to the skull and cranial syndesmosis models was separated into elements with the precision disc grinding wheel to minimize the material loss along the division lines. (Fig. 3).

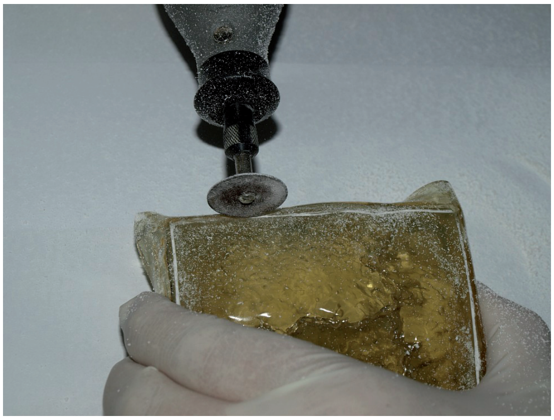

Fig. 3: *Cutting the contoured sheet (cranial syndesmosis model).*

Separating the hardened resin into segments does not affect the isochromatics lines distribution, nevertheless the image data is lost at the cutting line, so it is very important to minimize the material loss. Care should be taken not to damage the surface of the model. Figure 4 shows the optically sensitive coatings applied on the skull models. The coatings were applied on the Epidian 5 epoxy resin and the SLS rapid prototyping models.

The surface of the hardened resin coating needs to be smooth and transparent for the light ray undisturbed passage. The coatings removed from the model constructed with the SLS rapid prototyping method do not meet these criteria; their surface is slightly porous and requires additional polishing. Generally, such surface work is not recommended, nevertheless the test results in this case were not affected. It is recommended to limit the surface work to polishing in order to avoid removing too thick a layer of resin; it could become a problem during bonding if the thickness of elements is not the same. Although the SLS model was prepared prior to casting, smoothing was not entirely successful due to the atypical structure of the model after the powder sintering. The best results were achieved with resin rapid prototyping (SLA or PolyJet) models or epoxy resin vacuum casting models

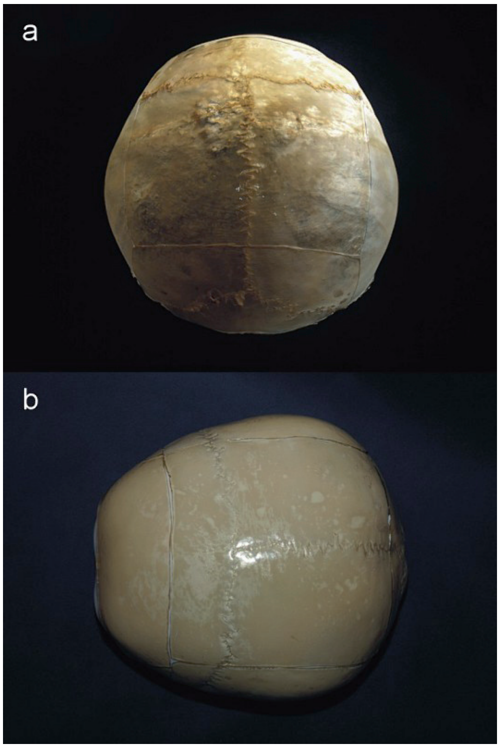

Fig. 4: *Optically sensitive coatings applied on skull models: a - Epidian 5 epoxy resin model, b - SLS rapid prototyping model.*

Fig. 5: *The optically sensitive coating and the upper skull and cranial syndesmosis models*

made with silicone mould.

The coatings removed from the skull and the cranial syndesmosis models are shown in Fig. 5.

The coating should be cleaned and prepared before installing on the surface of the test model. The appropriate adhesive should be used, in this case the PC-1 with the PCH-1 hardener (10:1 ratio) with the addition of aluminum powder. The aluminum powder creates a reflective layer under the optically sensitive coating (it will reflect the incident polarized ray (Fig. 6)). The adhesive layer should be 1mm thick and evenly applied on the whole surface of the tested area. The process of bonding is the last important step influencing the accuracy of the isochromatics lines reading. The excess adhesive should be bled from beneath the coating, along with the trapped air bubbles, so they cannot disturb the isochromatics lines reading (Fig. 7).

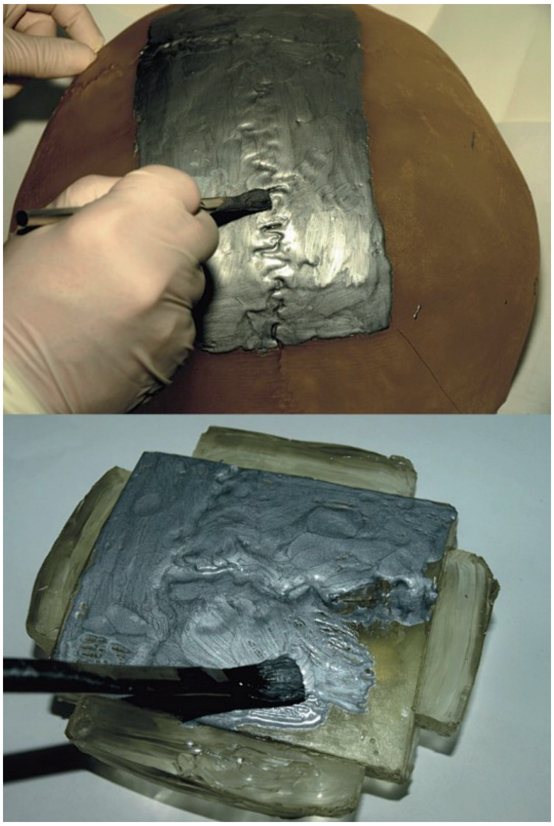

Fig. 6: *The PC-1 adhesive application on the upper skull and the cranial syndesmosis models.*

If the surface of the model is substantial and we need to apply several elements, bonding should be done gradually, to avoid contaminating the coating elements with the adhesive. In case of the 2:1 scale upper skull model, the upper and back elements were installed first. The installed elements were left to dry and then secured, and the remaining elements were installed later. Prior to installing the remaining coatings, the excess adhesive should be removed with the precision grinding tools (Fig. 8).

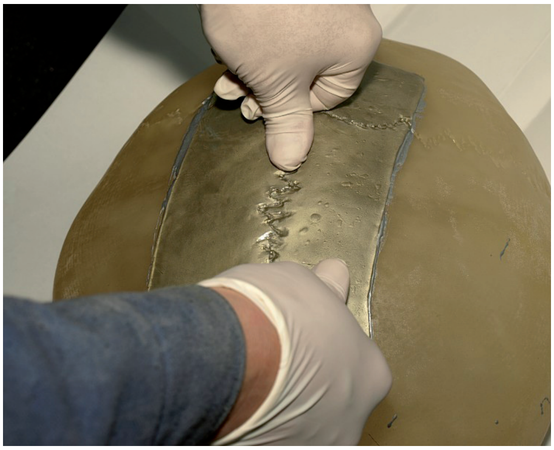

Fig. 7: *Fig. 7. The optically sensitive coating is bonding with the model.*

Fig. 8: *Removing the excess adhesive prior to the installation of the remaining coating elements.*

An optically sensitive coating is a tool to visualize the isochromatics lines distribution on the model surface. It means that it needs to be applied only on the area that is subjected to tests. Regardless of the size of the contoured coating, the isochromatics lines distribution should remain the same. This statement was verified when several models with various proportions of element sizes were produced (Fig 11).

Fig. 9: *Fitting all of the remaining optically sensitive coating elements on the skull model.*

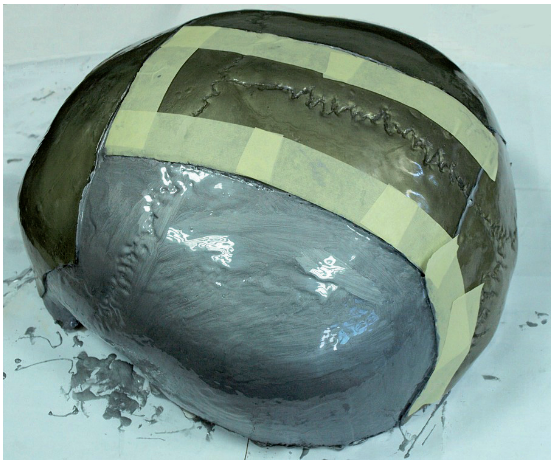

Fig. 10: *Installing the remaining contoured sheets.*

Fig. 11: *The finished models, with all of the optically sensitive coating elements installed.*

Fig. 12: *The finished model of the cranial syndesmosis with the optically sensitive coating.*

3. Results

A model is ready for analysis after few days; the surface of the model needs to fully bond with the optically sensitive coating. During tests, an external force is applied to a model, and the photoelastic effect is the measure of the applied load. An example of the isochromatics lines distribution is shown in Fig. 13.

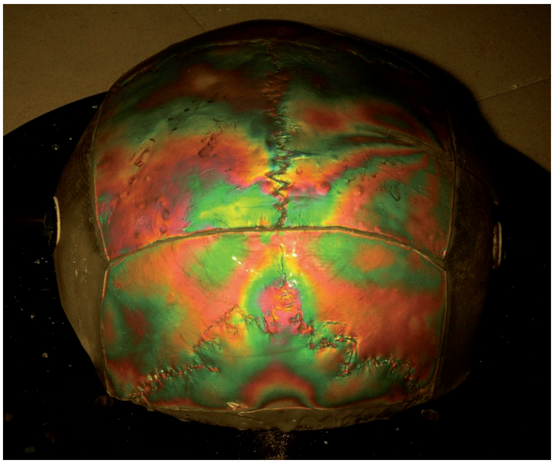

Fig. 13: *The isochromatics lines distribution on the upper part of skull model.*

It was proved that the best quality optically sensitive coatings were produced on SLA and PolyJet rapid prototyping models or vacuum casting models. The SLS models turned out to be inadequate because of the porous surface.

The 1:1 scale models were too small for the experiment. The skull model was so reduced that no cranial syndesmosis was visible. It was necessary to produce the skull models in 2:1 scale (SLS rapid prototyping and vacuum casting models), and cranial syndesmosis in 3:1 scale (PolyJet rapid prototyping model) and 4:1 scale (Solidscape model) to achieve satisfactory results. The isochromatics lines distribution images were clear and it was possible to perform a full analysis of a stress distribution in the cranial syndesmosis area.

4. Conclusion

The optically sensitive coatings preparation process needs an individual approach to every model case, due to shapes and size differences. In case of the cranial syndesmosis model it was crucial to determine the exact thickness of the coating, otherwise either the clarity of the optical effect, or the casting precision would be affected.

5. Acknowledge

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