PHOTOELASTICITY AS A RESEARCH TECHNIQUE FOR ANALYZING STRESSES IN DENTAL STRUCTURES

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THE primary purpose of the masticatory process is to apply forces to the nutritional substances which are taken into the mouth, thereby causing a reduction in their size. The mechanism for this action includes the medium of tooth structure which not only applies these forces directly to the food masses, but is itself subject to the effects of these forces.

In general, the effects of forces applied to a body are manifest in the development of internal stresses which are distributed in accordance with the direction of the applied forces, the manner in which the body is supported, and the shape of the body. Furthermore, these stresses are accompanied by internal deformations or strains within the body, and if their magnitudes are sufficiently large, permanent deformation and, ultimately, failure will ensue. Tooth structure and dental restorations are not exceptions to these rules. The structural design of normal tooth structures is such that they withstand the effects of masticatory forces. However, when tooth structure is removed and replaced by a dental restoration, the normal internal stress distribution is altered and the new stress situation will depend on the design of the cavity preparation. Furthermore, the shape of the restoration, which is also determined by the cavity preparation, is of considerable importance as to whether the restorative material will undergo permanent deformation or fracture.

In general, then, an evaluation of the internal stresses in both dental restorations and tooth structures should yield valuable criteria for successful design.

The consideration of stresses in dental structures is not a new concept. There has been considerable reflection concerning the design of dental restorations so as to avoid failure caused by internal stresses. Most of these efforts have resulted in generalities deduced from the theory of elasticity as applied to uniformly shaped structures and, therefore, leave much to be desired when confronted by the irregular shapes of dental structures. Empirical rules or criteria have developed over the years on the basis of clinical evidence and these have served to avoid the deleterious effects of internal stress magnitudes. However, since both the design and size of dental restorations are extremely limited by the biologic aspects of tooth structure, an exacting analysis is the only solution to the determination of an optimum structural configuration.

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When consideration is given to the irregular shapes of dental restorations, an experimental method of stress analysis is indicated since mathematical theories can be applied only to certain regular shapes. Photoelasticity is such an experimental method and it is the purpose of this paper to describe this method and its application to dental restorative design. The work of Noonan,[1] Castro,[2] and King[3]* is representative of the first concrete attempts to utilize this method in the solution of dental problems with regard to structural design.

A 3-dimensional analysis should be considered since most dental structures vary in shape and loading characteristics in 3 dimensions. However, for purposes of simplicity and convenience, the following discussion is for a 2-dimensional analysis, from which a 3-dimensional approach can be derived; where indicated. The engineering literature is quite thorough in its treatment of photoelasticity, and for more complete information, which is beyond the scope of this paper, reference is made to Frocht.[4, 5]

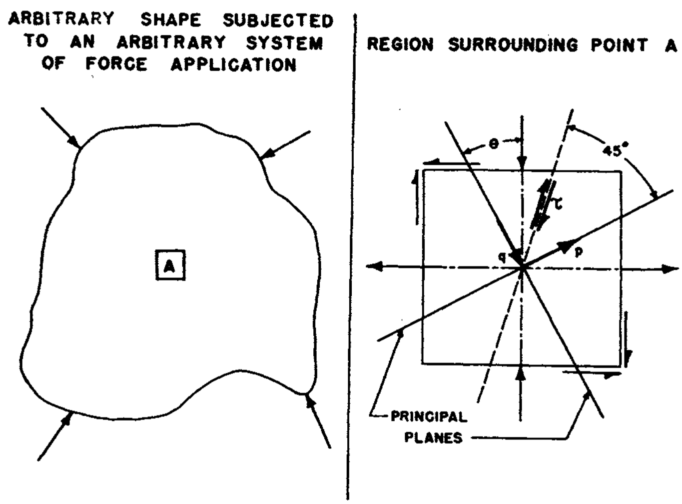


Fig. 1.—Stresses acting at a point in a body, illustrating the orientation of the principal or maximum stresses p and q as well as the maximum shear stress. τ.

PRINCIPAL STRESSES

The general procedure in structural design is to evaluate the maximum stresses which exist in a structure and relate these to the inherent strength properties of the materials which compose the structure. As a consequence, the first step in analysis would be to determine the maximum stresses. These stresses are illustrated in Fig. 1 for a 2-dimensional analysis. The sketch on the left-hand side is a schematic representation of a body of arbitrary shape subjected to an arbitrary system of force application (dental structures are simply specific cases of this general system). To investigate the internal stresses at any point in this body, that is, point A, it is convenient to magnify a small region surrounding this point. This situation is shown on the right-hand side

*Since preparation of this paper two additional references to this subject have appeared: Haskins, R. C., Haack, D. C., and Ireland, R. L., Study of Stress Pattern Variations in Class II Cavity Restorations as a Result of Different Cavity Designs, *J. D. Res.* 33: 757, 1954, and Watton, C. B., and Seven, M. M.: A Preliminary Report of Photoelastic Tests of Strain Patterns Within Jacket Crowns, *J.A.D.A.* 50: 44, 1955.

of Fig. 1. The stresses which are shown acting on the sides of the square element are those produced by the external force system and represent a general system of plane stress, that is, compressive, tensile, and shear type stresses are shown acting on this square element. The magnitude of stresses on an arbitrary plane passed through the element can be determined by resolving the stresses acting on the external sides of the element. As a further condition, if this plane is specifically oriented such that no shearing stresses are present, then the normal (perpendicular) stress to this plane is the algebraic maximum stress which exists at point A (corresponds in most cases to the largest tensile stress). Similarly, another plane, perpendicular to the aforementioned plane, exists upon which no shearing stresses act and the normal stress is the algebraic minimum stress at point A (corresponds in most cases to the largest compressive stress). These stresses are shown in Fig. 1 and their normal connotation is that p is the algebraic maximum stress and q is the algebraic minimum stress. The planes upon which these stresses act are known as principal planes. Furthermore, on a plane at 45 degrees to these principal planes, the acting shear stress τ is a maximum and the following relationship is valid.

$$\tau_{\max} = \frac{p - q}{2}$$

Although considerable work has been done in the field of engineering on the phenomenon of plastic deformation and fracture of solid structures, the actual relationship between the physical properties which describe the failure processes and the maximum internal stresses has not been defined exactly; this relationship being strongly dependent upon the type of material used and the way in which stress is applied to the material. Despite this inadequacy, knowledge of the maximum stresses serves as a firm basis for the analysis of structural designs.

PHOTOELASTIC METHOD

Photoelasticity is an experimental method for evaluating the stresses responsible for failure of a structure. The general procedure is to construct a model of the structure to be investigated from what is known as a photoelastic material. The direction and magnitude of the applied forces on the model, the way in which the model is supported, and the shape of the model must be similar to the conditions of the actual structure. The internal stresses in the model will then be similar to those existing in the actual structure regardless of material (assuming that the elastic limit has not been exceeded and that the original structure is a homogeneous isotropic material). This point establishes its validity from the absence of material physical constants from the stress distribution relationship of 2-dimensional systems. Experimental verification of this point also exists.

The temporary double refraction under stress of certain transparent isotropic materials (photoelastic materials) is utilized for photoelastic analysis. This property is such that an incident ray of light will be resolved into two rays which travel along the principal planes of the material at the point of incidence, the two rays traveling at different velocities and one emerging retarded with respect to the other. The amount of retardation is directly proportional to the difference between the principal stresses.

The photoelastic polariscope is used to measure the retardation, thereby measuring the difference between the principal stresses. The mechanism of measurement utilizes the property of light-wave interference (Fig. 2). The wave theory of light is used to explain this phenomenon. For simplicity, a monochromatic light source is shown (Fig. 2) which transmits light waves in all directions to the polarizer. The polarizer has the property of passing only those components of the incident light waves which are parallel to the polarizing axis. Consequently, plane polarized light is produced which impinges upon the stressed model made of a material exhibiting temporary double refraction under stress. Only those components of the incident wave which are parallel to the principal planes of the model at the point of incidence pass through, and these components are retarded in accordance with the degree of stress existing at the point in question. The two light waves then fall on the analyzer, which is physically the same as the polarizer except that its axis has been rotated 90 degrees. This would produce a dark field if no model were present. The

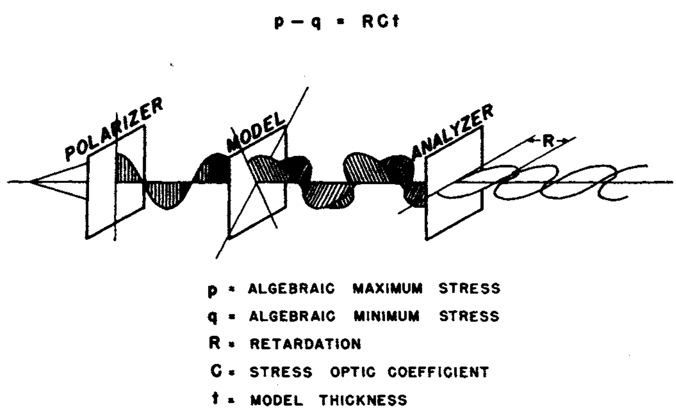


Fig. 2.—Schematic sketch of the operation of a photoelastic polariscope.

components of the incident light waves which are parallel to the polarizing axis of the analyzer are then passed through, and since they lie in the same plane, interference phenomena can occur. When the retardation is such that the paths oppose each other, a dark spot will appear, and when in-between conditions occur, some light will get through. Adjacent dark and light spots will then form alternate dark and light lines or fringes which are directly proportional to the principal stress difference existing in the model. The specific relationship of stress and retardation is given as:

$$p - q = aR.$$

Where a is a constant depending on the material from which the model was made and the thickness of the model, R is the retardation experienced by the light beam.

If a white light source is used, the light wave is made up of a number of waves having different frequencies. When one of the component waves is eradicated by interference, its complementary color remains and the entire effect is a spectrum of complementary colors. For example, when violet is extinguished, its complementary color of yellow is visible. Each color, then, represents a different degree of principal stress difference. In the field of photoelasticity, colored fringes were initially used for stress determination. However, the dark and light bands which result from the usage of a monochromatic source are employed today, almost exclusively, because of their superior quantitative accuracy. This is due mainly to the fading of the colored bands in the vicinity of high stress concentrations, caused by an overlapping of complementary colors.

The colored patterns, however, do serve to yield additional information necessary for the complete analysis of stress. This information is the direction of the principal stresses. Dark lines can be observed superimposed on the colored stress patterns. These occur whenever the plane of the incident polarized light is coincident with the principal planes of the point in question and as a consequence the light beam is not resolved and passes directly through the model. The analyzer, being perpendicular, nullifies this light, and dark spots appear, the locus of which are dark lines known as isoclinic lines. These lines, then, in representing the direction of the principal planes, are indicative of the directions of the principal stresses. By rotating the plane of the incident light beam, all of the isoclinic lines can be determined.

In order to evaluate the principal stresses individually, additional information is required. This individual evaluation is necessary to predict failure in accordance with accepted theories. Although there are several procedures available, based on the photoelastic data, an experimental method exists which enables the determination of the sum of the principal stress (p + q). The merit of this auxiliary method is that it is a separate source of principal stress information, independent of the photoelastic data. It is based on the measurement of the lateral deformation of the model under stress and the relationship which exists is:

$$p + q = SK.$$

Where K is a constant depending on the physical constants of the photoelastic materials being used and the thickness of the Model, S is the lateral deformation of the model under stress.

Having determined the value of p − q by the photoelastic method and the value of p + q by the lateral deformation method, the individual value of p and q can be easily evaluated. This information, together with the direction of the principal stresses as determined by the isoclinic lines, is sufficient for the complete analysis of the significant stresses developed in dental structures as a result of applied occlusal forces.

APPARATUS AND TEST PROCEDURE

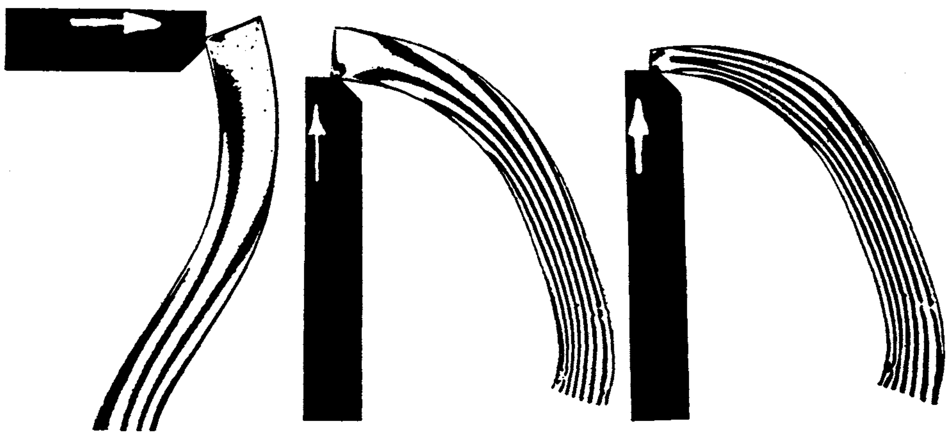
The photoelastic polariscope which has been designed and assembled at the Physical Research Laboratory of the University of Michigan School of Dentistry uses white light or monochromatic light lamps interchangeably as a light source, an aperture approximating a point source at the focal length of the lens system, a filter used with monochromatic light source, a condensing lens to produce parallel rays in the field of the model, a quarter-wave plate to produce circular polarized light which eliminates the isoclinic lines, a beam type of loading mechanism with a water tank at the end, by means of which the load is adjusted, catalin 61-893 model material, a second quarter-wave plate to resolve emerging light waves, a polaroid analyzer to resolve light waves into the same plane, a collecting lens to converge parallel field rays, and a camera to record patterns.

A lateral extensometer is used for measuring lateral deformation which yields the subsequent (p + q) value. This device, designed to incorporate the Tuckerman Strain Gage, was patterned after Peterson and Wahl's[6] extensometer. It can record a dimensional change of less than 1 micron.

Fig. 3.—Stress distribution in a buccolingual section of a molar tooth subjected to an occlusal load for (*A*) a normal tooth, (*B*) one restored with an amalgam restoration, and (*C*) one restored with a gold inlay preparation.

The procedure of test is as follows and refers specifically to the handling of Catalin 61-893, a photoelastically sensitive plastic, which is available in roughly ground plates: the shape of the structure to be analyzed is drawn on a piece of Catalin, which is then cut moderately close to this outline; the model blank is then ground to a uniform thickness on successively finer polishing papers and finish-polished on a metallographic polishing wheel; the model is then trimmed to the final outline. Since the stress-retardation relationship is dependent upon the model thickness, it is imperative that this factor remain constant. For this reason, the procedure given here is followed since the polishing operation tends to round the edges of the model and, therefore, must be done before the final outline is cut. A masking tape can be used to protect the polish of the model when the final outline is cut. The model is then placed in the loading mechanism with a supporting structure and load application designed to approximate, as closely as possible, the actual conditions of the structure being investigated. The pattern is then observed and photographed.

In interpreting the stress pattern it is important to realize that each dark or light band is a locus of points representing constant shear stress or constant principal stress difference. In addition, the bands which appear will be of different orders such that the first order band will represent a given value of stress while the second order band will represent twice the value of stress as the first order band, and so on. There are ways of determining what order band exists at a point in question but the simplest method is to observe the pattern formation while loading and the order of bands can thus be easily determined.



A. *B.* *C.*

Fig. 4.—Stress distribution in a partial denture wrought clasp under the action of (*A*) masticatory loads, (*B*) the force necessary for removal, and (*C*) the force necessary for removal but using a tapered clasp.

APPLICATIONS OF PHOTOELASTICITY IN DENTISTRY

A number of examples were prepared to indicate the types of dental problems for which this method is especially suited. They were arbitrarily chosen and are representative rather than inclusive examples.

In Fig. 3 is shown a buccolingual section of a mandibular right permanent first molar subjected to an occlusal load. The support for the tooth was made of aluminum and shaped to approximate the bone structure. The tooth section was sealed to the aluminum mold with impression compound. The load was applied through a round pin to approximate the opposing cusp. These pictures show the stress distribution of a normal tooth section (*A*), a section restored with an amalgam type restoration (*B*), and a section restored with an inlay type restoration (*C*). If the bands are counted from the tips of the cusps which are free from stress, we find a concentration of 4 light bands at the pulp horn on the left for the normal tooth section. For the amalgam restoration, the concentration is about 5½ whereas the inlay restoration is about 7 bands. Since these bands are directly proportional to the shear stress, it can be concluded that the placement of the restoration has significantly increased the stress concentration at the point under consideration and furthermore that this increase is dependent upon the design of the cavity preparation.

In Fig. 4, a partial denture-wrought clasp used on a bilateral type of restoration is analyzed. The buccal view of the clasp is shown (*A*) with the force applied as a result of resorption in the saddle area and a consequent tipping of the restoration under vertical occlusal loads. This force was determined by assuming the amount of deflection which would occur at the end of the clasp under the conditions previously stated. The occlusal view of the clasp (*B*) is shown with the force necessary to remove the restoration. This was determined by the amount of deflection required to allow the clasp to escape the contour of the abutment tooth. The same view is shown (*C*) with the exception of a tapering of the terminal third of the clasp. This particular case is presented because of the high incidence of clasp failures which occur in practice. The preliminary conclusions which can be drawn from these illustrations are that the stresses induced in the clasp are greater upon removal than under the action of masticatory loads and tapering the terminal third of the clasp slightly reduces the stresses induced in the clasp but in addition reduces the retention. It would appear that a relatively large cross-sectioned clasp which would reduce the stress at the point of attachment would prevent failure, and if a taper were to be employed, the retention could be brought to within desirable limits.

SUMMARY

It has been indicated that the analysis of stresses in dental structures would establish valuable criteria for the design of cavity preparations and dental restorations. The experimental method of photoelasticity was described in theory and practice, and two examples were presented to show the application of this method to the analysis of stress in dental structures. This method of analysis was shown to be particularly applicable to dental problems because of the irregular shapes of dental structures.

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