A PHOTOELASTIC STUDY OF STRESS CONCENTRATIONS PRODUCED BY RETENTION PINS IN AN AMALGAM RESTORATION

A Thesis

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ABSTRACT

The purpose of this investigation was to compare stress concentrations produced by different types of pins in an amalgam restoration under occlusal load.

It was decided to perform a two-dimensional photoelastic stress analysis of a model simulating a Class II amalgam restoration containing a pin. The pin simulated two conditions; one in which it would bond with the amalgam and the other in which it would not. Preliminary tests revealed that the magnitude of stresses produced by a pin was affected by the nature of the support given to the pin by the dentin. A pin which was well gripped by the dentin possessed a greater axial stiffness and produced a greater stress concentration in the amalgam than a pin which was loosely fitted. In clinical situations, the nature of the support of dentin to a pin could vary because of different pin-anchoring techniques employed. The simulation of correct physical and mechanical relationships of components in a photoelastic model would be essential in order to obtain meaningful results. Due to the lack of available data, it was found necessary to determine values for axial stiffness of retention pins in dentin by different methods.

Two types of pins, smooth and self-threading, were fixed in specimens of human dentin by different methods to represent five conditions of anchorage. The three methods, similar to those encountered in clinical practice, were represented by using friction-locked, self-threading and smooth-cemented pins. The other two methods represented theoretically extreme conditions, a loose-fit pin in an oversized channel and a built-in pin, threaded and cemented in an undersized channel. The latter two methods were included to test the validity of a theoretically calculated range of axial stiffness values. A specific compressive load was applied to the top of the pin and the resultant axial deflection was measured with specially constructed apparatus. Three separate measurements of axial deflection were made on each pin and twenty pins for each condition of anchorage were tested. Average values of axial stiffness were calculated from these measurements. Statistical analysis of variance and t-tests were performed to determine whether a significant difference existed between the stiffness values.

A two-dimensional photoelastic stress analysis was performed on a simulated model of a Class II restoration containing a pin, capable or incapable of bonding to amalgam and possessing properties of low or high axial stiffness. A comparison between the number of isochromatic fringes produced by each condition of the pin under identical load levels was made. Similarly, the number of isochromatics produced at the top of the pin was compared to those produced at the point of load application.

The built-in pin exhibited three times greater axial stiffness than the loose-fit pin. For the three clinically used anchoring conditions, the self-threading pin exhibited the greatest axial stiffness, the cemented pin the next greatest and the friction-locked the least. Axial stiffness values for these pins were in approximate ratios of 7:6:4.

Unbonded pins produced three times the amount of stress concentration produced by bonded pins. Pins possessing high axial stiffness produced fifty percent more stress concentration than those with low axial stiffness. The pin which possessed high axial stiffness and which did not bond to the amalgam produced the greatest stress concentration in the amalgam. At any given load level, the stress concentration produced at the top of a pin was one-third of that produced at the point of load application.

Results indicate that axial stiffness values of pins, utilized clinically, differ significantly from each other. The stress concentration produced by a pin is influenced by the axial stiffness of the pin and the presence or absence of a bond between the pin and the amalgam. The maximum amount of stress concentration around the top of the pin was found to be forty percent of that produced at the occlusal surface. Excluding other variables, such as the cusp-restoration contact area and the geometry of the top of a pin, such a stress concentration is not likely to cause failure of a restoration under idealized conditions. In clinical situation several factors are likely to vary, as a result, chances of a failure of a restoration due to the stress raising effect of a pin, especially that of unbonding type, do exist. Utilization of electroplated pins capable of bonding to the amalgam is recommended in order to minimize stress concentrations in amalgam restorations.

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INTRODUCTION

Silver amalgam is the most widely used restorative material in Dentistry. Retention of an amalgam restoration depends almost entirely upon the geometry of the cavity preparation. The absence of adhesion between the tooth structure and amalgam is responsible for one of the major difficulties in restorative dentistry, namely, retention of a large restoration in an extensively mutilated tooth.

During the last two decades, a technique has evolved whereby retention is improved through the agency of metallic wires or pins. The technique consists of anchoring stainless-steel or noble-metal pins in channels drilled in dentin and condensing amalgam around and over the projecting pins.

Various types of pins have been tried in order to obtain the maximum benefit. Currently, three methods for anchoring different types of stainless-steel pins to the dentin are commonly employed in clinical practice. These methods consist of forcing a pin to a friction lock, cementing a pin, and screwing a self-threading pin. The first two methods utilize either a smooth or serrated stainless-steel pin.

The early inference that pins would reinforce amalgam was later proven to be incorrect. In fact, it has been demonstrated that pins have a weakening effect on an amalgam restoration. It is possible that development of stress concentrations by pins may contribute to this weakening effect. Up to the present time, the presence of such stress concentrations has not been reported.

REVIEW OF THE LITERATURE

Historically, gold screws were first suggested by Davis[1] for the retention of gold foil restorations. Storer[2] reported the use of nickel screws in conjunction with copper-amalgam restorations. It was not until Markley's[3] introduction of the "reinforcement technique" that the use of stainless-steel pins for retention became popular.

Markley[3,4,5] and other investigators[6,7,8,9] claimed that, besides providing retention, metallic pins also reinforced amalgam restorations. Wing[10] and Going[11,12,13] however, found that the strength of amalgam specimens which contained stainless-steel pins was less than that of specimens without pins. Welk and Dilts[14] and Moffa et al.[15] also collected sufficient experimental evidence to conclude that pins, in fact, reduce the strength of amalgam.

Wing[10], in his metallographic investigation of amalgam specimens containing pins, observed characteristic voids between the pin and the amalgam matrix. During condensation of the amalgam, mercury is extruded and accumulates around the pin. Because stainless-steel is relatively inert, this free mercury is drawn back into the amalgam matrix during the progress of the setting reaction and voids are thus produced. Wing also suggested that these voids may be the reason for failure of amalgam specimens at lower stress levels.

Additional experimental evidence[16] substantiates the presence of voids around the non-reactive or non-bonding stainless-steel pins.

Silver pins, used by Cecconi and Asgar[17], reacted well with mercury. However, failure occurred within the pins and no increase in the strength values of amalgam specimens containing such pins was observed.

Further attempts at obtaining a strong metallurgical bond by using stainless steel pins plated with gold or copper were equally unsuccessful.[17,18]

Duperon[19] demonstrated that the quality of the bond between the core wire and the electroplated layer of silver or copper was very poor. Although a stronger bond could be obtained between the silver or copper and the amalgam, he concluded that early failure would result because of the weak nature of the bond between the base wire and the electroplated layer.

Platinum-gold-palladium pins, electroplated with sterling silver, were used by Duperon and Kasloff[20] for their investigation of the effects of different types of pins on the strength of amalgam. They found lower strength values for specimens prepared with stainless-steel pins compared to specimens containing electroplated noble metal pins. They also demonstrated, by means of electron micrographs, the presence of voids between stainless-steel pins and the amalgam. Such voids were virtually absent around electroplated pins, which presumably formed a metallurgical bond with the amalgam.

Duperon[19] has also demonstrated the existence of excellent adaptation of the electroplated layer of silver to the base wire of platinum-gold-palladium. He postulated that voids, existing between the stainless-steel pins and the amalgam matrix, act as additional stress raisers.

Retentive properties of three types of stainless steel pins, friction-locked, cemented and self-threading, were investigated by Dilts[21] and Moffa[15,22]. They found that self-threading pins were the most retentive in both dentin and amalgam. Friction-locked pins were the least retentive in amalgam and cemented pins were the least retentive in the dentin.

Duperon[19] performed withdrawal tests on pins embedded in amalgam. He found that the degree of retention for serrated pins was greater than that for electroplated pins. The retention value for smooth stainless-steel pins in amalgam was found to be negligible.

Lee[23], Hendry[24], and Holister[25] have described various methods of experimental stress analysis, including the photo-elastic technique employed in engineering science. The object of stress analysis is to determine and improve the mechanical strength of structures. Hendry[26] has discussed several aspects of photoelastic stress analysis. It is the most versatile method for stress analysis and has the advantage of maintaining a direct relationship with the true physical nature of the problem. A specialized branch of photoelastic technique permits the analysis of stresses in three dimensions.

Noonan[27] applied the photoelastic technique to dental research for the first time. He used Bakelite to prepare photoelastic models of different cavity shapes.

Haaskins et al.[28] used Catalin for the preparation of photoelastic models in their studies of the effect of pulpo-axial line angles on stress distribution. They concluded that there was a marked reduction in stress concentration when the pulpo-axial line angle was rounded.

Currently, epoxy resins are the most commonly used materials for the preparation of photoelastic models[29]. Mahler and Peyton[30] have discussed general applications of photoelastic stress analysis technique to dental structures.

Mahler[31], on the basis of his investigations, concluded that failure of the restoration at the isthmus was due to tensile stresses. He suggested that the isthmus should be placed as close to the axial wall as possible. He also advocated preparation of a sloping axial wall and a flat pulpal floor in order to minimize the tensile stresses produced in the restoration.

Guard et al.[32] studied bucco-lingual sections of Class II cavity forms and concluded that a gentle rounding of the pulpal wall and line angles reduces stress concentration.

Many other investigators[33-37] have utilized the photoelastic method to demonstrate stress-raising factors, such as sharp line angles and point angles. Various cavity forms which permit better stress distribution have been evolved as a result of their investigations and are currently being adapted in clinical practice.

The photoelastic method has also been used to analyze stresses in other dental structures. Colin et al.[38] studied stress concentrations in full crowns and concluded that sharp angles at gingival shoulders should be avoided.

Robinson[39] studied stresses produced in the tooth structure resulting from expansion of dental amalgam. He investigated cavities with either parallel or undercut walls and concluded that the difference in stresses developed was not significant, providing the amalgam was properly manipulated.

Craig et al.[40-45] performed extensive analyses of stress distributions in inlays, crowns and abutment teeth.

The three-dimensional photoelastic technique has been employed in dental research by some investigators. Lehman and Hampson[46] studied stress patterns in jacket crowns fabricated from Araldite. They found that the stress near the gingival part of the crown was ten times greater than that at the incisal edge, thus explaining the crescent-shaped fractures seen to occur near the cervical margins of jacket crowns.

Johnson[47], in his three-dimensional photoelastic analysis of molar teeth with different cavity forms, found that the inclusion of irregularly shaped pulp chambers did not affect the stress distribution. Another investigation performed by Johnson et al.[48] revealed that the rounding of the pulpal wall and line angles reduced the stress concentrations by thirty to forty percent.

Lehman and Meyer[49] undertook a three-dimensional photoelastic stress analysis of contact areas of adjacent teeth. On the basis of their findings they postulated that mechanical stresses in the contact areas may be a direct cause of initiation and propagation of early caries.

Stresses produced by retentive pins in the tooth structure have been recorded by Craig et al.[44]. Standlee et al.[50] identified stresses produced in the dentin during the installation of different types of pins. They observed that self-threading pins produced the greatest amount of stress during their installation which could cause fracture of the dentin.

STATEMENT OF THE PROBLEM

Many research workers have investigated the deleterious effect of pins on the strength of amalgam specimens. On the basis of their findings they have concluded that weakening of amalgam is caused by the stress-raising effect of pins. They have further hypothesized that voids, formed between non-reactive stainless-steel pins and the amalgam matrix, are additional stress-raisers. On the other hand, the metallurgical bond between the reactive electroplated pin and amalgam is said to improve the shear performance of the pin-amalgam structure.

Thus far, research in this field has concerned itself with the effect of pins on the strength of amalgam specimens. Knowledge about the effect of pins on stress concentrations in an amalgam restoration is lacking.

It is therefore proposed to investigated what differences in stress concentrations may be produced by different types of pins and to determine whether these stress concentrations significantly affect the strength of an amalgam restoration.

METHODS AND MATERIALS

General Considerations

The distribution of stresses in a pin-retained amalgam restoration produced by a compressive load acting on the occlusal surface is governed largely by two sets of factors, geometric and material. The geometric factors include relative dimensions of the pin and amalgam matrix. The material factors include mechanical properties of stainless-steel, amalgam and dentin. Young's Modulus for stainless-steel is approximately sixteen times greater than for either amalgam or dentin, as illustrated in Table I. A stainless-steel pin in a relatively less rigid medium of amalgam, therefore, acts as a stress raiser and produces stress concentration in the amalgam.

Stress analysis may be performed by one of three methods, of which one is computational and the other two, experimental. The computational method utilizes the technique of finite element analysis which could be employed to determine internal stresses in a restoration. Such a technique requires the performance of a large number of computations which involves expensive computer time. In the second method, an experimental one, the original structure is subjected to appropriate loading conditions and the resultant strain is measured by utilizing devices such as electronic strain gauges, brittle lacquer or a laser beam. The relatively small dimensions of the retentive pin and amalgam restoration in a human tooth make the use of

Table I

Values of Young's Modulus*

Material	Young's Modulus Nw/m^2
Stainless-steel	21×10^{10}
Amalgam	1.38×10^{10}
Dentin	1.17×10^{10}

*Values are converted from the original[51] foot-pound-second units to the metre-kilogram-second units.

electronic strain gauges extremely difficult. The brittle lacquer technique and laser holography measure surface deformations only. Although it may be possible to relate such surface deformations to internal stresses by computational methods, they are highly complicated. A three-dimensional stress analysis of a restoration, even with laser holography would be extremely difficult. The third method utilizes scale models of original structures fabricated from photoelastic or other suitable materials.

Experimental stress analysis is simplified by adapting a two-dimensional approach although it is not truly representative of the three-dimensional situation in the oral environment. In this respect, a two-dimensional photoelastic technique is probably the most versatile of the methods. It enables one to obtain an overall picture of the shear stress distribution throughout the body under investigation. It is not suitable for detailed calculations of stresses in a pin-retained restoration because of variables such as complicated tooth morphology and restoration geometry. The purpose of this investigation was aimed at determining only the relative stress values under various conditions, therefore, a high degree of accuracy in calculating particular stresses was not required.

Physical and mechanical relationships between the pin, amalgam and dentin affect the stress distribution in a restoration under occlusal load. In order to obtain meaningful results it is essential to maintain these relationships in proportion to the scale of the photoelastic model. Evaluation of these relationships under clinical conditions is a difficult task because of the complex nature of the tooth-restoration geometry. A simplified model of an amalgam restoration with a retentive pin will be utilized to discuss some pertinent aspects of stress distribution.

Figure 1 illustrates a Class II restoration in a molar tooth with a retentive pin anchored in the gingival floor. Figure 2 illustrates a simplified model of a portion of this restoration. The tooth structure surrounding the amalgam is omitted and its possible effect on the stress distribution is disregarded for the sake of simplicity. For further simplication, a flat surface is substituted for the complex occlusal geometry upon which a compressive load is applied at point "A". In this simplified form the "restoration" is represented by a cylinder of amalgam resting on a cylinder of dentin, with the pin fixed in the center. The long axis of the pin coincides with that of the amalgam-dentin cylinder. Dimensions of the pin and the overlying amalgam are similar to those encountered in an average clinical restoration.

For a given amount of load, the stress value at "A" will be maximum in comparison to that in any other part of the model. The level of stress will gradually diminish as

Figure 1. Schematic diagram of a Class II restoration with a retention pin.

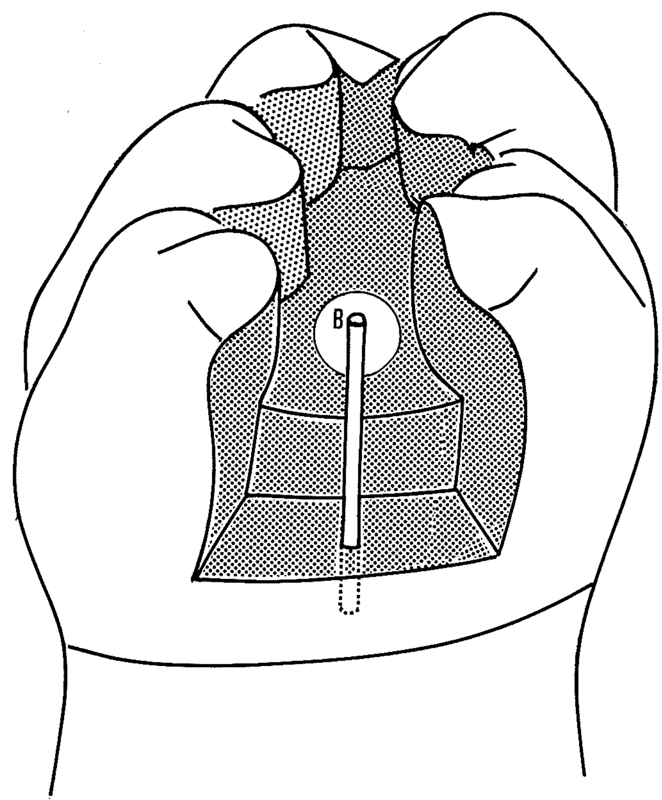

Figure 1

Figure 2. Simplified model of a pin-amalgam restoration.

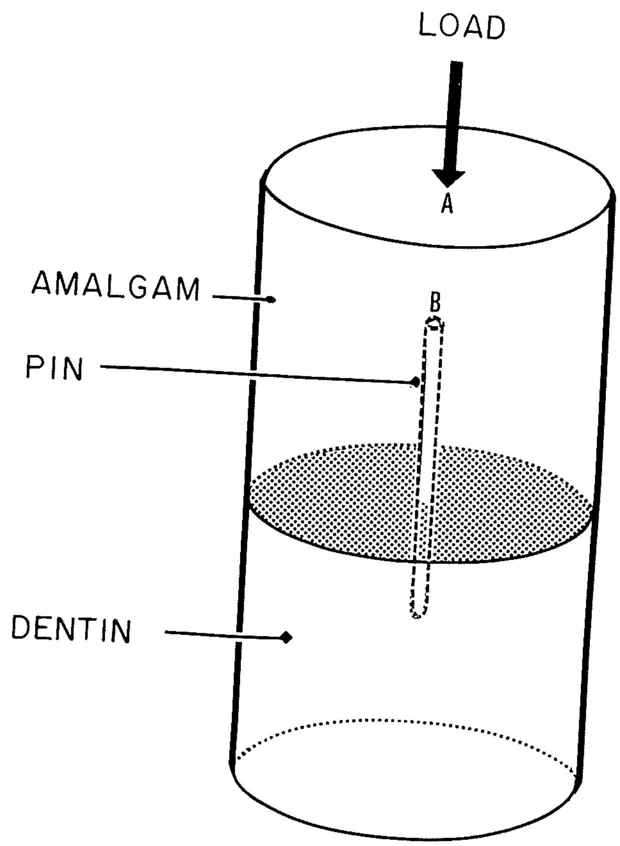

Figure 2

the distance from "A" increases. The stress around the top of the pin, area "B", will be a certain percentage of the stress level at "A".

By applying this reasoning to the photoelastic model it is possible to make a direct comparison between the stress levels produced at the point of load application and around the top of the pin. Knowing that the maximum stress level will be at the occlusal surface, the degree of stress concentration around the top of the pin could be estimated. Its possible harmful effect on the restoration could thus be evaluated. In addition, a comparison between stress concentrations produced by different types of pins is possible.

The pin in Figure 2 is approximately 5.5 mm. in length and 0.56 mm. in diameter. The diameter of the pin is small in relation to the model. The bending deflection is proportional to the fourth power of the diameter, hence, the lateral component of a non-vertical load will produce a negligible amount of lateral stresses in the pin, which can be completely disregarded. The compressive load may be assumed to act along the long axis of the pin, thus, the resultant deflection of the top of the pin in the axial direction will be of significance as far as the stress-raising effect is concerned. In quantitative terms, axial stiffness of the pin will affect the magnitude of the stress concentration produced in the amalgam.

The length to diameter ratio is termed slenderness and for the pin in this model it has been determined to have a value of 10. The stress-raising effect due to the axial stiffness of the pin, may be quite considerable because of the high slenderness of the pin.

The axial stiffness of a pin anchored in dentin would depend upon Young's Moduli of the dentin and stainless-steel and the nature of the support given by the dentin to the pin. The latter would be determined by the manner in which the pin is anchored to the dentin. Theoretically, there are two extreme conditions of pin anchorage in dentin which would permit calculation of axial stiffness of pins. In the first condition, a pin is seated in an oversized channel, as shown in Figure 3(a). It rests on the bottom of the channel and is assumed to receive no shear support from the walls. In the second condition, a pin is completely bonded to the dentin so that it is uniformly supported in shear along its sides and in compression at the bottom, as illustrated in Figure 3(b). The pin in the first condition may be referred to as "loose-fit" and the one in the second condition, "built-in".

A given amount of load will produce more axial deflection in a "loose-fit" pin than in a "built-in" pin. Conversely, the amount of load required to produce unit axial deflection will be less in the case of the "loose-fit" pin than with the "built-in" pin. Hence, the axial

Figure 3. Two theoretical conditions of pin-anchorage.

(a) "Loose-fit" pin in an oversized channel, supported at the bottom only.

(b) "Built-in" pin supported at the bottom and along the sides of the channel.

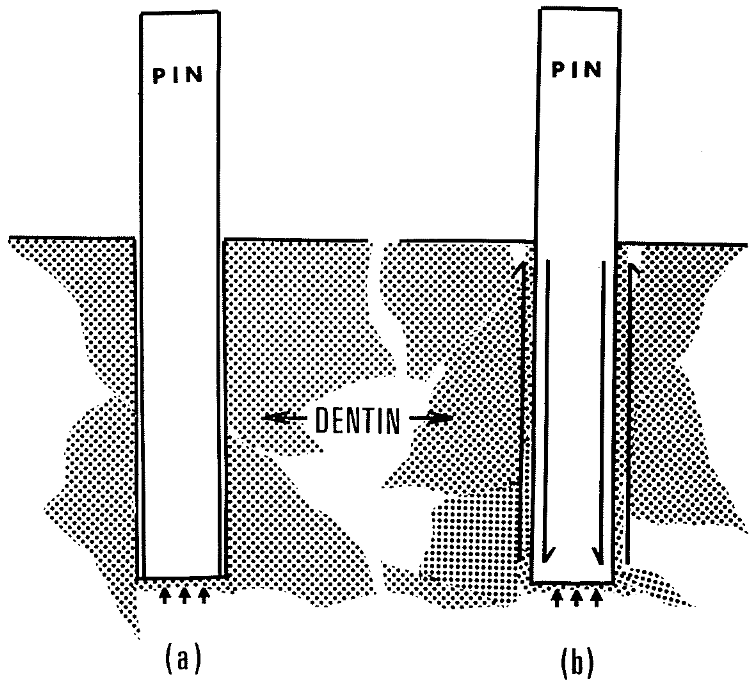

Figure 3

stiffness of the "loose-filt" pin would be less than that of a "built-in" pin.

Values for axial stiffness were calculated from the data presented in Table I. They were 1.8×10^{6} Nw/m for the "loose-fit" pin and 10×10^{6} Nw/m for the "built-in" pin.

The commonly used clinical techniques of anchoring pins to dentin involve one of the three methods, namely force-fitting a pin to a friction-lock into an undersized channel, cementing a pin into an oversized channel and screwing a threaded pin into a channel of an appropriate size. It is reasonable to expect that the nature of the support given by the dentin to pins, anchored by different methods, will be different in each case. Consequently, values of axial stiffness of pins and the degree of resultant stress concentrations produced in amalgam would differ accordingly. Values for axial stiffness should fall within the range defined by those calculated for theoretically extreme conditions of "loose-fit" and "built-in" pins.

Part I - Experimental Determination of Axial Stiffness for Retentive Pins in Human Dentin

Dentin Specimens

Specimens of human dentin were obtained by horizontal sectioning of third molars which were randomly selected from wet cold storage. An approximate similarity of shape and size were the only criteria considered in selection. Age, location and duration of storage were not taken into account. The sectioned tooth was mounted in auto-cure acrylic which was later ground to a disc about 7 mm. thick and 30 mm. in diameter. Coronal and root dentin were exposed at the two flat surfaces of the acrylic disc and these surfaces were polished with #4-0 emery paper. A specimen is illustrated in Figure 4.

The two types of pins tested were smooth stainless-steel*, 0.56 mm. in diameter, and self-threading stainless-steel** with an outer diameter of 0.78 mm. and core diameter of 0.60 mm. Three conditions for the smooth pins and two conditions for the self-threading type, as described below, were investigated.

Condition 1: Loose-fit. A smooth pin was seated in an oversized channel, 0.58 mm. in diameter.

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* TRU-CHROME Orthodontic Wire - Rocky Mountain Dental Products, Willowdale, Ontario.

** THREAD-MATE-SYSTEM Whaledent Inc., Brooklyn, N.Y.

Figure 4. Dentin specimen.

(a) horizontally sectioned molar tooth.
(b) self-threading pin anchored in dentin.
(c) cold-cure acrylic base
(d) markings made to facilitate positioning the transducer probe at a distance of 3 mm. from the pin in four directions.

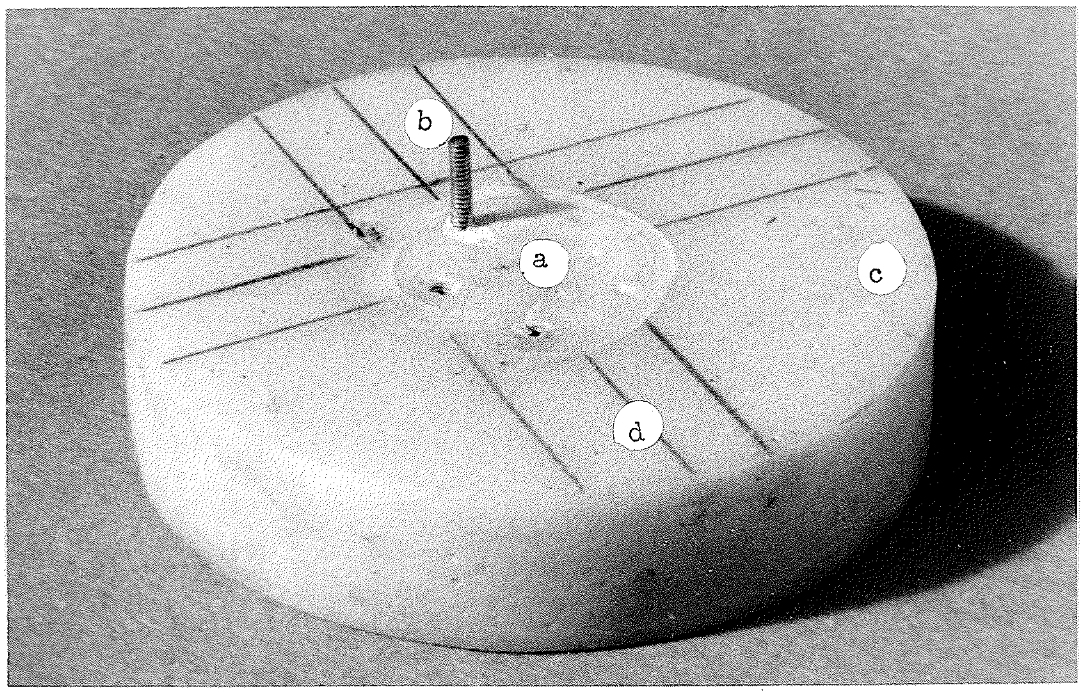

Figure 4

Condition 2: Friction-locked. A smooth pin was forced into an undersized channel, 0.53 mm. in diameter.

Condition 3: Smooth-cemented. A smooth pin was cemented with zinc oxy-phosphate cement into a channel, 0.57 mm. in diameter.

Condition 4: Self-threading. A threaded pin was screwed into a channel, 0.68 mm. in diameter as recommended by the manufacturer.

Condition 5: Self-threading-cemented. A self-threading pin was screwed and bonded into a channel similar to condition 4.

All smooth pins were cut to a length of 5.5 mm. and their ends ground flat, before anchoring them in the dentin. A self-centering twist drill of appropriate size was fitted into the chuck of a porcelain-facing drill press* and was utilized for forming channels with a controlled depth of 3 mm. The channels were located approximately half-way between the pulp chamber and the dentino-enamel junction.

The friction-locked pins were gently forced into the undersized channels. In the case of Condition 3, the channel was filled with zinc-oxy-phosphate cement and a cement-coated pin was inserted into the channel. The self-threading pins were screwed into their channels using a wrench supplied by the manufacturer. For Condition 5, the

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* PORCELAIN FACING DRILL, Model MD-11 - Mardel Industrial Products, Monrovia, California, U.S.A.

pin was threaded into the channel and then removed. The resultant threaded channel was filled with a mix of autocure acrylic and the pin, coated with the fluid resin, was rescrewed into the channel. This procedure allowed the fluid acrylic to fill the spaces between the threads of the pins and those of the channel, after which it polymerized. Thus, the condition simulating a completely built-in pin was closely approximated.

The upper end of each pin was slightly domed to ensure axial loading of the pin. Elastic bending of the pin was found to introduce significant errors if a close approach to true axial loading was not achieved.

Problems of Measurements

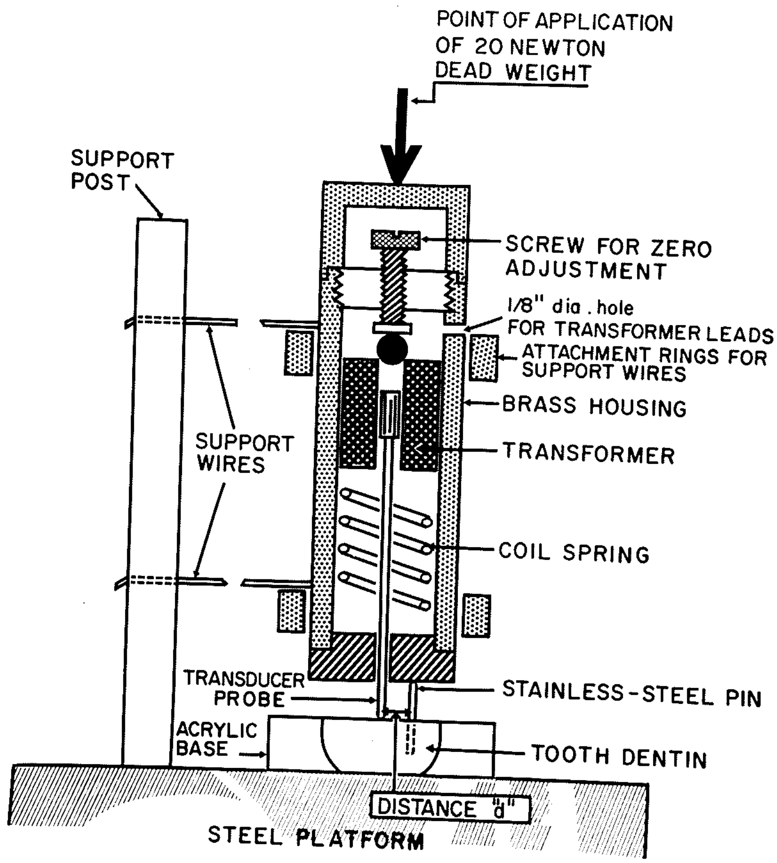
The difficulty with measurements of this nature is that of applying a loading force to and measuring the resultant deflection of a pin of such small dimensions. An ideal procedure would be to apply the load to a longer pin and measure the deflection from the surface of the dentin to an appropriate point on the pin. Such a method would, however, create problems of unwanted deflection due to elastic bending properties of a long pin. An apparatus for measuring the pin deflections, utilizing optical interferometry and possibly laser optics was considered but was rejected primarily because the appropriate apparatus was not readily available. Consequently, a more direct mechanical method of measurement was chosen. A high-resolution electromechanical transducer, available in the Civil Engineering Laboratory, was selected as the instrument for micro-measurement.

Measuring Apparatus

The apparatus, constructed for measuring deflections is shown schematically in Figure 5. A linear-voltage differential transformer is housed in a cylindrical brass body, to which is fitted a device for the mechanical adjustment of zero. The load on the top of the pin is applied by placing dead weight on top of the transducer housing. Axial deflection of the pin will alter the relative positions of the transducer housing and the probe. Figures 6, 7, and 8 illustrate the loading device, the measuring apparatus and the specimen, respectively.

It is desirable to limit the movement of the transducer housing so that it is free to move only in a vertical axial direction. Ideally, the housing should have zero constraint in this direction so that the force applied to the tip of the pin remains the same as the dead weight placed on the top. In all other directions, it should be completely constrained to avoid spurious deflections due to canting of the housing. In practice, the latter cannot be achieved but it is possible to provide a high level of constraint in all but the axial direction. Such constraint is provided by six steel wires, three at the top of the

Figure 5. Schematic diagram of deflection measuring apparatus and specimen.



SECTIONAL VIEW
OF
DEFLECTION MEASURING APPARATUS
AND A SPECIMEN
(not to scale)

Figure 5

Figure 6. Complete assembly, consisting of loading device, measuring apparatus and specimen.

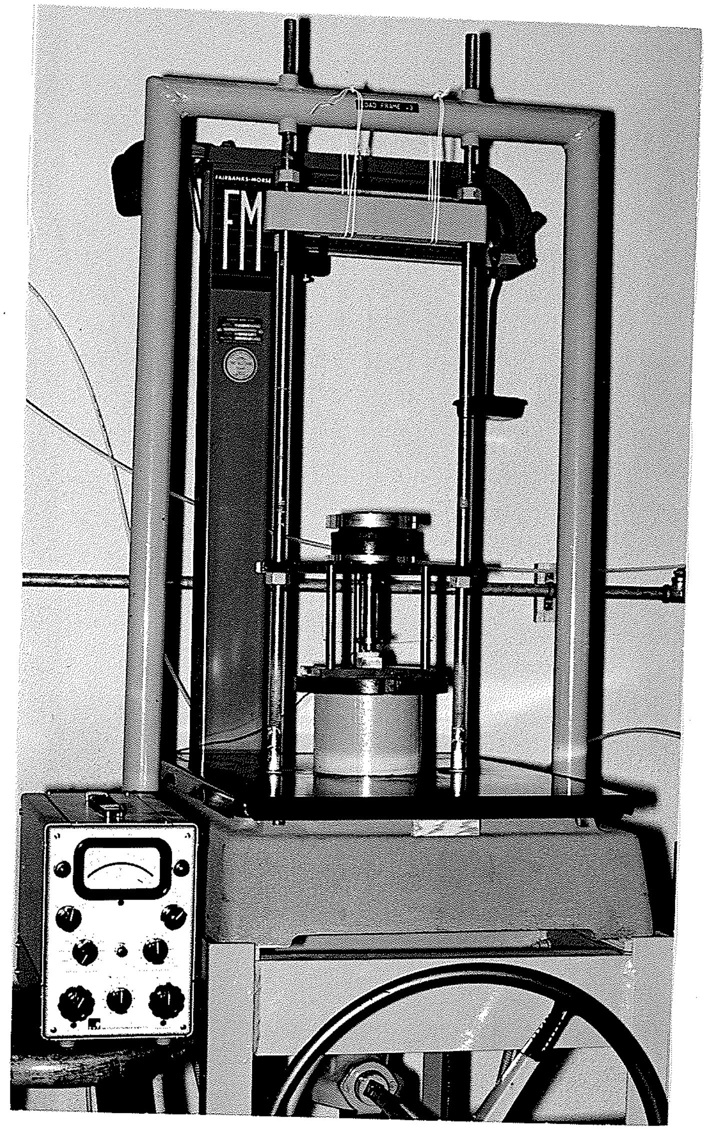


Figure 6

Figure 7. Measuring apparatus.
(a) 4.5 Newton dead weight
(b) transducer housing
(c) specimen

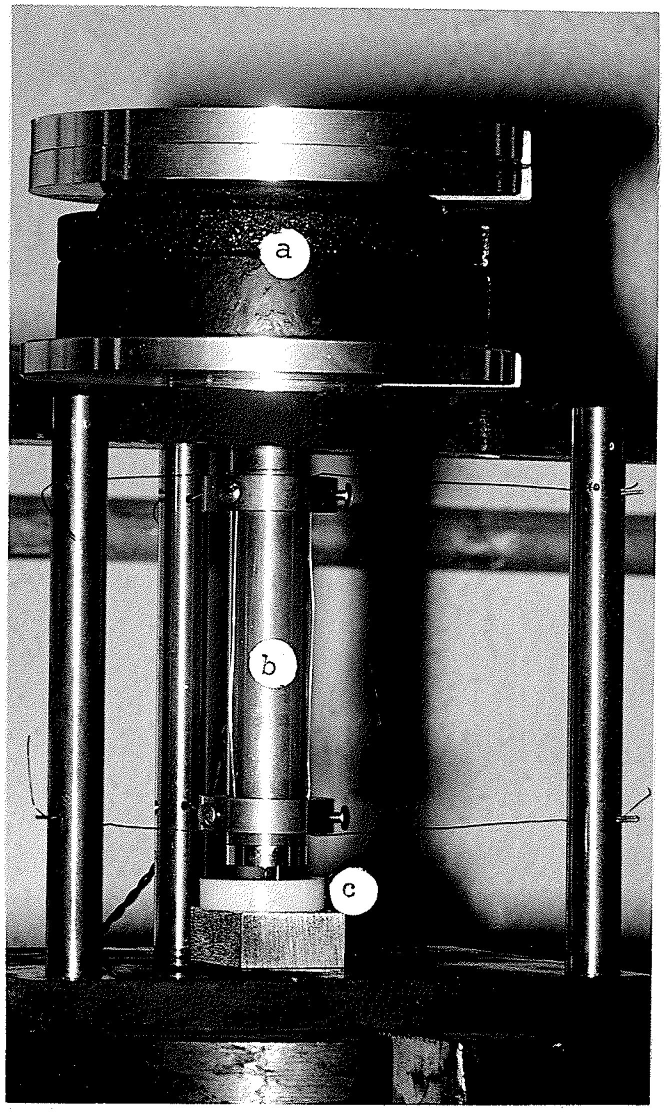


Figure 7

Figure 8. Specimen and measuring apparatus.

(a) acrylic base holding the dentin specimen
(b) pin anchored to the dentin
(c) probe of the transducer
(d) loading platten of the transducer housing

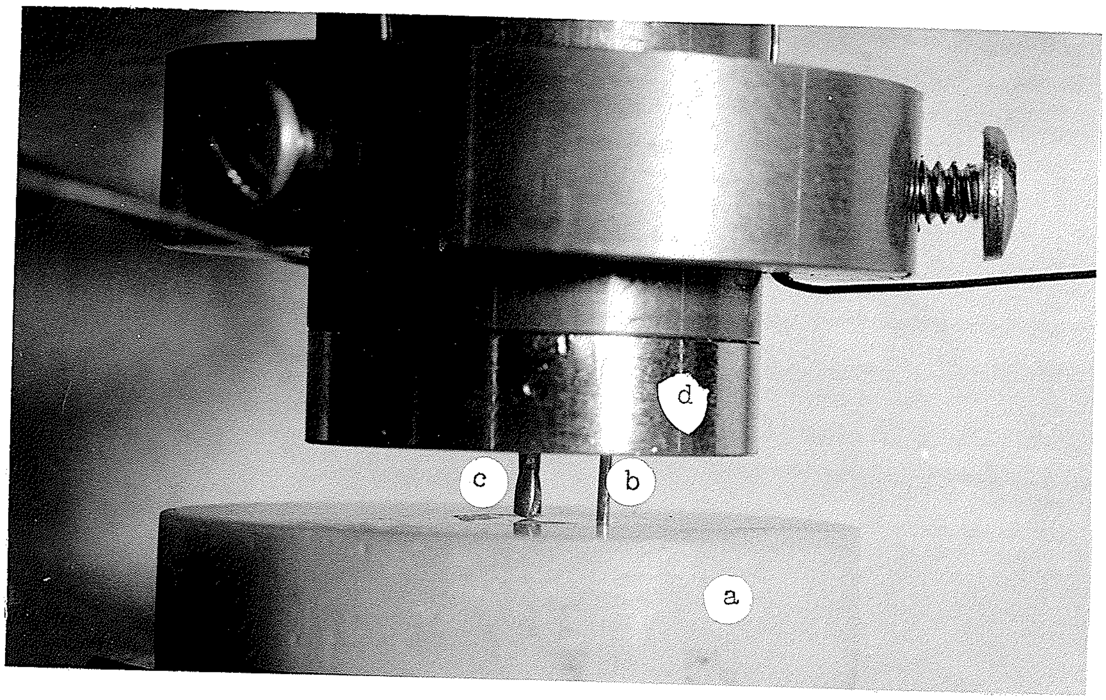


Figure 8

housing and three at the bottom, attached to three rigid posts, as shown in the plan view of the apparatus (Figure 9). Practically, it is impossible to avoid some axial constraints. The range of vertical movements of the transducer housing was not expected to be more than 11 μ. Calculations showed that under the worst conditions the axial constraint was less than one percent of the applied load and was therefore negligible.

The linear voltage differential transformer* housed in the apparatus has a linear displacement range of ±1 mm. The most sensitive range of the meter** is 0 - 1.0 μ for a full scale deflection of the needle. Thus, when the transducer is used with the meter on its most sensitive range, it is capable of resolving to 0.005 μ. Most of the measurements were taken with the meter set at the 0 - 10 μ range and hence a resolution of 0.05 μ was possible.

An accuracy of better than five percent in the determination of stiffness values could be expected when a load of 20 Newton dead weight was applied to the top of a pin. Although a larger applied load would increase this accuracy, it would also increase the local stresses in the dentin to an unrepresentative high level. It was therefore considered desirable to limit the maximum stress to a level which would be substantially below the ultimate strength of

* Linear Voltage Differential Transformer - Hottinger Baldwin, Darmstadt, West Germany.

** Type KWS/T-5 - Hottinger Baldwin, Darmstadt, West Germany.

Figure 9. Top view of deflection measuring apparatus.

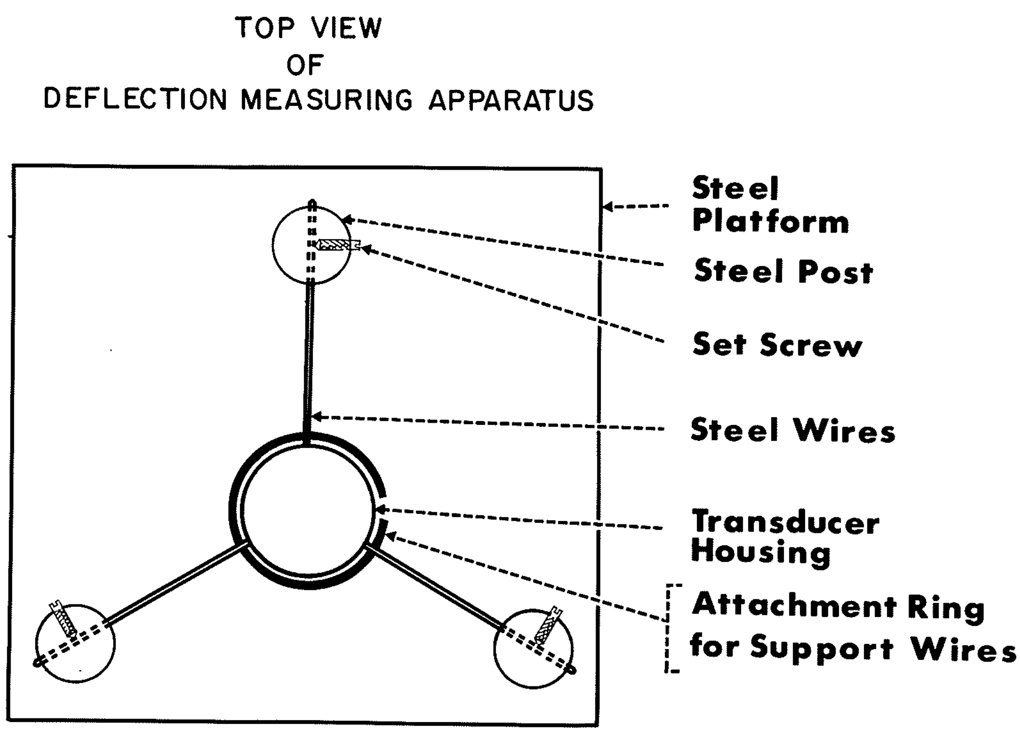

TOP VIEW
OF
DEFLECTION MEASURING APPARATUS
Steel Platform
Steel Post
Set Screw
Steel Wires
Transducer Housing
Attachment Ring for Support Wires

Figure 9

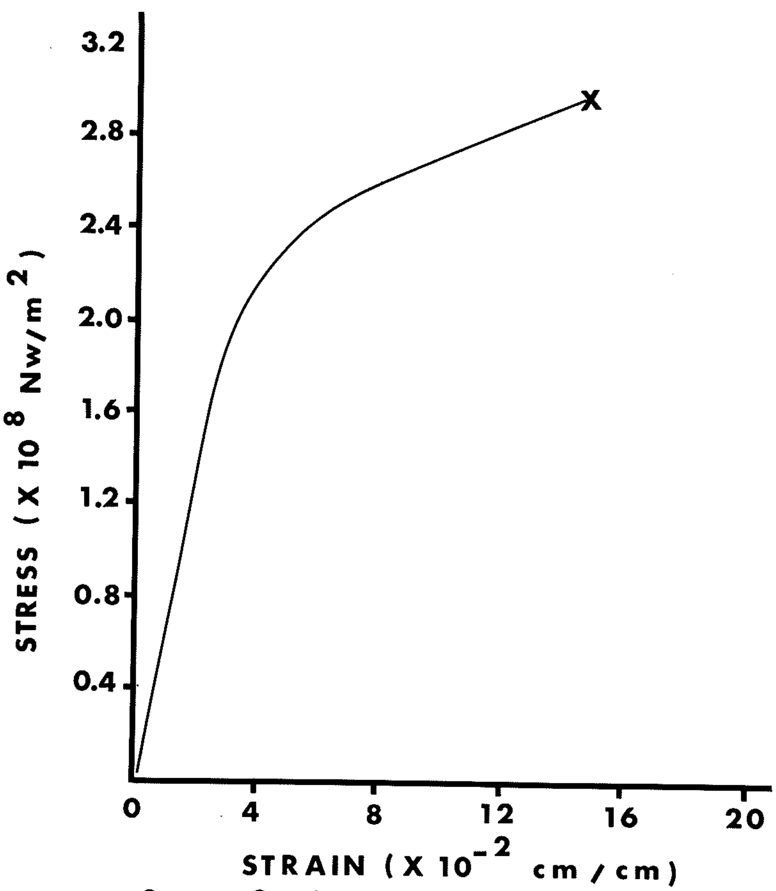
strength of the dentin. At an applied load of 20 Newton, the maximum stress would likely be approximately 1.02×10^{8} Nw/m^{2} which is only thirty percent of the ultimate strength of the dentin, as well as being well within the proportional limit of the dentin as illustrated in Figure 10[52].

Correction Factors and Calibration

A number of deformations and relative movements occur in a measuring technique of the kind described here. These require assessment and appropriate corrections must be made on the observed readings.

Canting of the specimen: The specimen may rotate through a very small angle relative to the axis of the measuring probe due to an asymmetrical loading. There must be a substantial separation of the pin from the probe, consequently any small rotation of the specimen will introduce an error in the measurement of deflection. Since the angle of rotation is very small, it is reasonable to assume that this effect is linear. This error is assumed to be of the same magnitude for two measuring points which, relative to the pin, are equidistant but diametrically opposite to one another. If the error at one point is positive, the one at the opposite point would be negative and vice versa. Thus, if four measurements spaced around a circle described from the center of the pin are taken, it is reasonable to use their average value as a means of

Figure 10. Stress-strain curve for dentin in compression*
*Values are converted from the original[52] foot-pound-second units to the metre-kilogram-second units.



Stress-Strain curve For Human Dentin In Compression

Figure 10

cancelling the effect of slight canting of the specimen.

Canting of transducer housing: The forces acting on the transducer housing are such as to produce a couple. Thus, in applying a dead load to the top of the housing, the resulting vertical force is equilibrated by the non-axial resisting force of the pin and a couple is produced. This couple must be resisted by an equivalent couple generated by unequal tensions in the wires which support the housing. As explained previously, these wires and the supporting posts cannot provide infinite rigidity. Consequently, the generated couple induces some angular rotation of the housing axis from the vertical. The resultant error in measurement is proportional to the square of the distance separating the probe and the pin. This follows from the simple fact that for a given load, the couple generated and its effect on measured deflection are proportional to the quoted distance. Experimental determination of the error resulting from canting of the transducer housing yielded the following empirical relationship:

$$e = 26d^2 + 4.4$$

"e" is the error in observed deflection in microns and "d" is the distance between the axes of the pin and probe in millimeters.

Separation between the pin and the probe: Selection of the distance "d" in Figure 5, separating the pin from the transducer probe, is a matter of compromise. Any axial deflection of a pin which is supported by the walls of the channel will be accompanied by deformation of the dentin surface immediately surrounding the pin. If the transducer probe is positioned too close to the pin, it will record an error because of the displacement of the dentin. Deformation of the dentin surface at a distance of more than five pin-diameters is extremely small and therefore can be ignored. On the other hand, the error due to slight tilting of the transducer housing increases as the square of the distance separating the pin and the transducer probe increases. By reducing the distance "d" to a minimum, it is possible to minimize this effect. A reasonable compromise under these circumstances was found to be a distance of 3 mm. between the pin and the probe.

Deflection of transducer housing: As is evident from Figure 5, the load is applied to the top of the pin via the transducer housing and the reference point for measurement is set by adjusting the screw located at the top of the housing. Consequently, a small deflection is introduced by the elastic deformation of the transducer housing under load. This deformation could be avoided by constructing a double-shell housing for the transducer. Such a deflection is linearly related to the magnitude of the load and a correction factor can be computed and applied to the observed results. This correction was calculated and experimentally determined to be equal to 0.008 μ/Nw.

End effect. The microscopic projections on the top of the pin and on the surface of the loading platten (Figure 8) are plastically deformed during initial loading. Plastic deformation continues until the local stress value reaches a magnitude which is just below the yield point of steel. It is necessary to subject the pins to a number of load-unload cycles to ensure that the plastic deformation process is complete before the deflection measurements are recorded.

Elastic deformation of these projections which follows the initial plastic deformation is a localized phenomenon, known as the end effect. It is a constant function of the load and is independent of the dimensions of the pin. The end effect is unrepresentative of the clinical situation where the pin is loaded via the amalgam. Hence, the magnitude of the end effect should be determined and a correction should be made to the observed values of deflection. A simple experiment was performed for this purpose as described below.

A steel pin, 20 mm. long and 1.08 mm. in diameter, was placed in a hole, 17.5 mm. deep and 1.1 mm. in diameter drilled in a rectangular steel block. This pin-block combination is a replica of a specimen as far as load and deflection are concerned. The expected deflection of this pin under load may easily be calculated and compared with the measured result. The difference in the two values would be an estimate of the correction factor to be applied. The experimental procedure was extended in order to eliminate other previously described corrections and to obtain more accurate value for the end effect. While keeping the overall length of the pin and all other factors constant the experiment was repeated with the pin cut into two, three, four, and five pieces. In this way, it may be assumed that the only significant variable is the number of steel to steel interfaces, therefore, the number of end effects.

Results of this experiment are shown graphically in Figure 11. From this it may be deduced that the end effect for one interface is 1.6 μ when a 20 Nw loading force is utilized.

Calibration. Extrapolation of the curve to "zero joints", as illustrated in Figure 11, gives a close correspondence with the theoretically predicted deflection of the pin. This indicates that the overall calibration of the instrument is satisfactory.

An additional experiment was performed with the steel block-pin combination to provide further proof of satisfactory calibration of the instrument. In this case, pins of different lengths were placed in holes, each drilled to a depth which allowed 2.5 mm. of the pin to protrude above the surface of the steel block. Separate measurements of

Figure 11. End effect: Linear relationship between number of joints and amount of deflection.

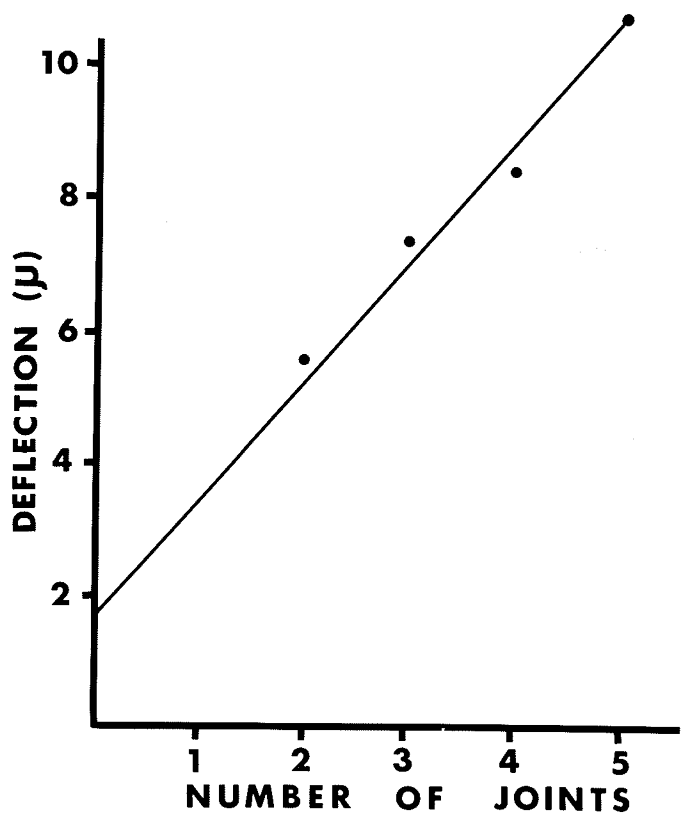


Figure 11

the deflections of each of these pins were compared with their respective theoretically calculated values. A close agreement between these provided a check on the calibration of the instrument. The calibration results are illustrated in Figure 12.

Method

The pin was loaded and unloaded by gently lowering and raising the dead weight on the housing to allow for initial plastic deformation at the pin-platten interface. The deflection value obtained after the first two or three load-unload cycles was found to be consistent and was taken as valid. The same procedure was repeated with the pin positioned at four points around the probe, on two mutually perpendicular axes. The average of the four readings thus obtained was taken as the measured deflection. In this way the effect of slight canting of the specimen under load is cancelled. Three such measurements were taken on each of twenty samples for one condition of pin anchoring. Thus, the final mean deflection for each condition is the result of an average of sixty measurements.

Figure 12. Calibration: Linear relationship between length of pin and amount of deflection.

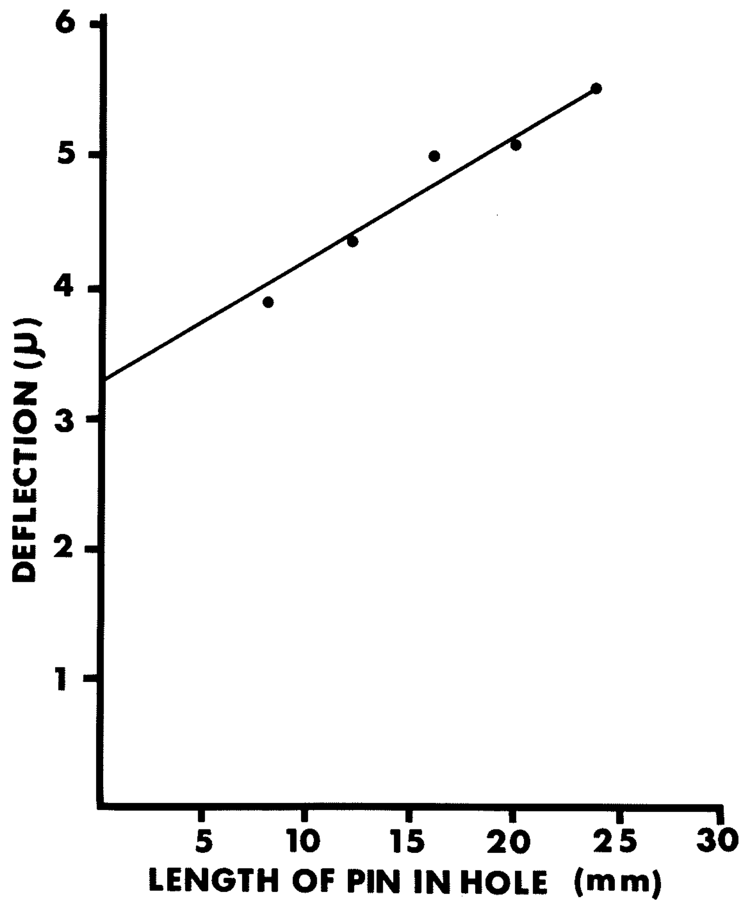


Figure 12

Part II - Two-dimensional Photoelastic Stress Analysis of a Pin-retained Amalgam Restoration

A magnified outline of a mesio-distal cross-section of a Class II restoration was traced on a sheet of perspex. A template was fabricated by cutting along the outline with a band saw. The edges of the template which represented the occlusal and the proximal contours of the restoration were filed smooth. All straight surfaces, namely distal, pulpal, axial and gingival were machined with a milling cutter. The template was fixed on a 6 mm. thick sheet of photoelastic epoxy resin* with double-stick tape. The resin sheet was cut with a band saw leaving about 5 mm. of excess material around the template. The final contouring of the model to the shape of the template was accomplished by trimming off the excess material with a high speed router. The model was separated from the template and examined in a polariscope. Stresses in the model, induced by cutting and machining, were eliminated by annealing the model at a specific time-temperature cycle recommended by the manufacturer of the resin. The model was again observed in the polariscope to ensure that it was virtually free of all stresses which might interfere with the results.

The basic model was used first to simulate the

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* Photoelastic sheet, Type PSM-5, Photolastic Inc., 67 67 Lincoln Hwy., Malvern, Pa. 19355.

control restoration without a pin. The same model was then modified and used to simulate a restoration with a pin.

The base used for mounting the photoelastic model represented the dentin and was fabricated from a 6 mm. thick sheet of perspex. The edges which would be in contact with the model were carefully machined so as to obtain the most accurate fit possible.

Control model. The model was attached to the perspex base with double-stick tape to eliminate minute irregularities and to obtain an even contact between the edges. This control model was identified by letter "a".

Model with a pin. In order to obtain a correct simulation in the photoelastic model it was essential to select material representing the pin with an appropriate modulus of elasticity. The elastic moduli of stainless-steel and amalgam are in the ratio of 16:1[51]. A satisfactory pin replication was achieved by using an aluminum insert machined in the following manner. The cross-section of the insert was I-shaped throughout its length except for the two ends where it was rectangular. This geometry produced a pin with the same relative modulus of elasticity to the resin as that of stainless-steel to amalgam. The machined insert was 126 mm. in length, 8 mm. in width and 6 mm. in thickness.

A rectangular slot, approximately 75 μ wider than the aluminum pin, was machined in the model and the base about halfway between the axial wall and the mesial surface. When the model and the base were assembled these slots were aligned with each other and their combined length was equal to that of the pin. A steel hoop, fabricated from a strip of sheet metal, was bolted to the base. A pair of brass wedges, inserted between the edge of the base and the hoop and compressed by a C-clamp, allowed for clamping of the pin in the slot. Figures 13 and 14 illustrate the entire model-pin-base assembly. With this arrangement it was possible to make the pin loose fitting or tight fitting in the base, thus simulating two extreme conditions of low and high stiffness of the pin in dentin. Four different conditions of the pin, with respect to its axial stiffness and bonding to the amalgam, were simulated in the basic model and were identified by letters "b", "c", "d", and "e" as follows.

(b) *Low-stiffness-unbonded:* A thin layer of quick-setting epoxy adhesive was spread on the top of the pin which was then inserted into the slot in the model. The adhesive, allowed to set for one hour, ensured a uniform contact between the top surface of the pin and the model. The model was attached to the base in the same manner described for the control model.

(c) *High-stiffness-unbonded:* The model remained essentially the same as in condition "b" except that the pin was clamped in the base by pressing together

Figure 13. Photoelastic model assembly simulating low-stiffness pin.

Figure 14. Photoelastic model assembly simulating high-stiffness pin.

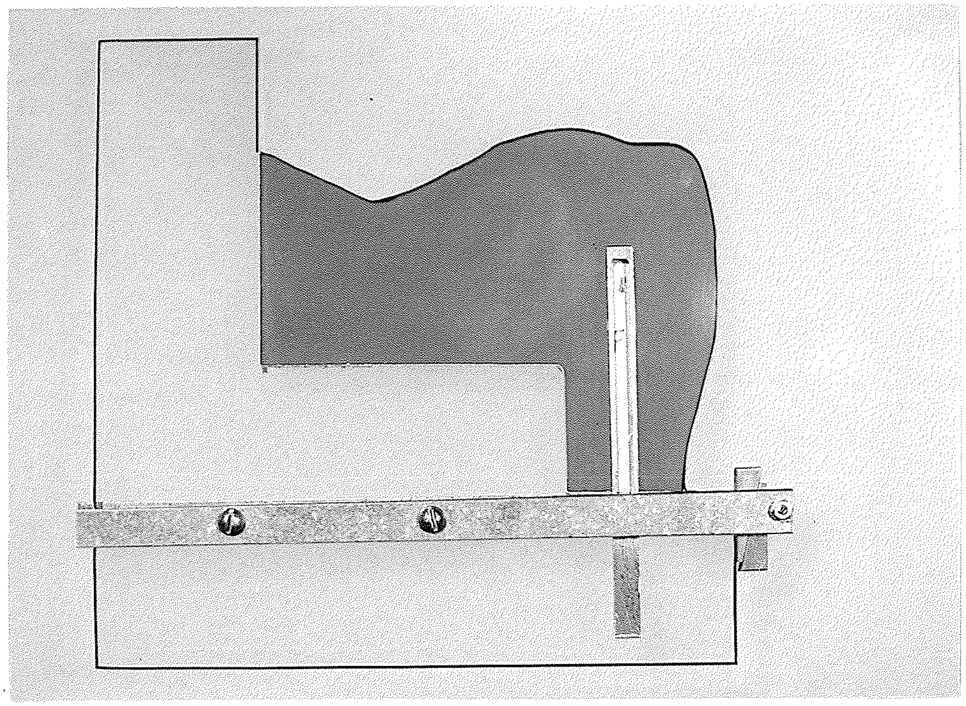

Figure 13

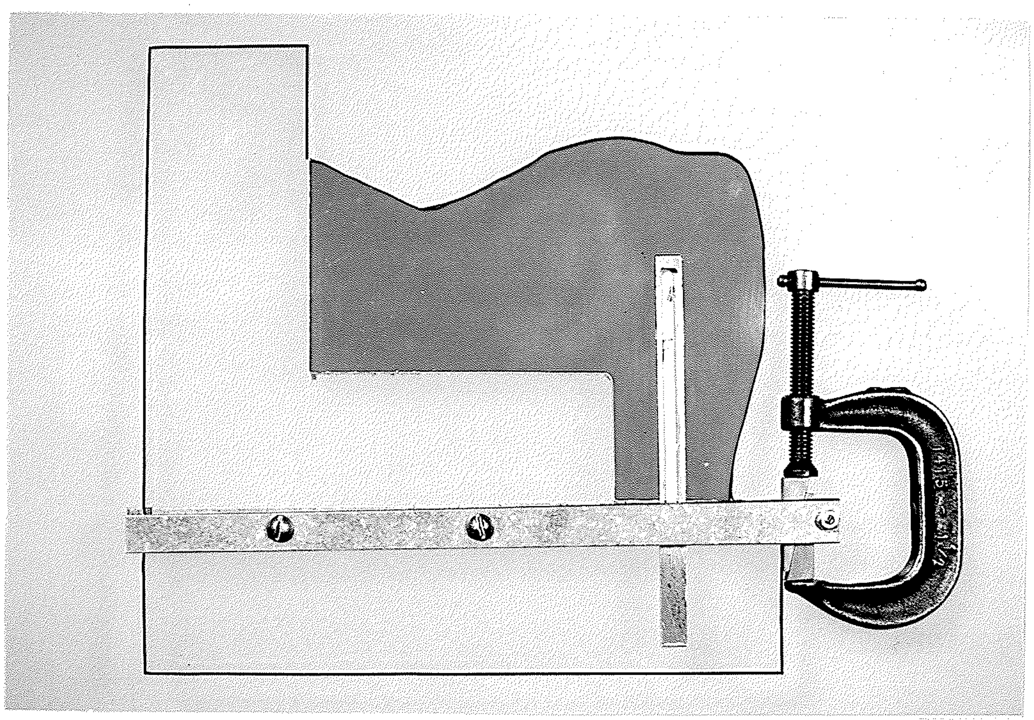

Figure 14

a pair of brass wedges inserted between the base and the hoop, as shown in Figure 14.

(d) *Low-stiffness-bonded:* The model and pin were separated from each other and from the base. The surfaces of the pin which were in contact with the model were roughened to produce shallow grooves to provide a good mechanical bond with the adhesive. These surfaces and the corresponding surfaces of the model were coated with slow setting epoxy adhesive and the pin was positioned in the slot of the model with light pressure. The adhesive was allowed to set for twenty-four hours before the model was fitted to the base.

(e) *High-stiffness-bonded:* The model remained the same as in condition "d" but the pin was clamped in the base as described for condition "c".

Calibration Disc

A circular disc, 875 mm. in diameter, was cut from the remainder of the photoelastic sheet which was utilized to fabricate the model. It was annealed in a manner similar to that employed for the model.

Method

A loading apparatus, a transmission polariscope consisting of a light source, a polarizer, two quarter-wave plates and an analyzer and the photographic equipment comprised the armamentarium for observing and recording the light and dark fringes produced in the model. The model was positioned vertically in the loading frame as illustrated in Figure 15 and the load was applied through a cylinder of bakelite at a specific point on the occlusal surface. The circumference of the cylinder simulated the curvature of an opposing cusp. Two levels of loading force, namely 355 Nw and 710 Nw, were applied in succession. The time-lapse between successive loading operations was kept constant and to a minimum for all model conditions. The light and dark fringes, produced in the models at each load level, were recorded photographically on Kodak High Contrast Copy film. A 35 mm. camera with an extension tube, a 135 mm. telephoto lens and a green filter were employed for this purpose.

Calculations

Circularly polarized white light, passing through a photoelastic model under load, produces multicolored fringes called isochromatics. If a monochromatic light source is employed, or if the colored isochromatics are observed through a green filter, alternate light and dark isochromatic fringes are obtained. The principal stress differnce, $(\sigma_1 - \sigma_2)$ along an isochromatic fringe has a constant value. Isochromatics are also referred to as lines of constant shear stress.

Figure 15. Polariscope

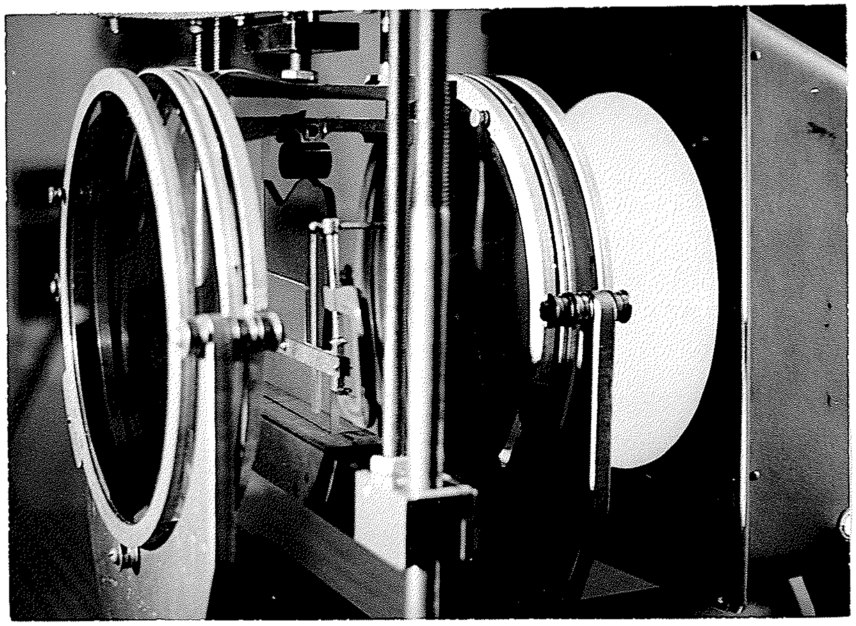

Figure 15

Figure 16 is a schematic diagram of isochromatics produced in the photoelastic model of a restoration containing a pin. The isochromatic fringes at "A" originate from the point of application of the load and those at "B" are produced by the stress-raising effect of the pin. All other factors being equal, the greater the amount of stress, the greater will be the number of fringes. The number of fringes at "A" and "B" will be affected by the occlusal load. In addition, for a given amount of load, isochromatic fringes at "B" are presumed to be affected by the axial stiffness of the pin and the presence or absence of a bond between the pin and the epoxy model.

A comparison of the number of isochromatic fringes, produced at "B", in different model conditions, will indicate relative differences between the stress-raising effects of different types of pins. A comparison made between the number of fringes at "B" and "A", in each model condition, will indicate the degree of stress produced by a pin in terms of the percentage of the stress produced at the point of load application.

An isochromatic fringe which is farthest away from the origin is referred to as the first order fringe, the one next to the farthest is the second order fringe, and so on. The order of fringes increases towards the origin. The fringe nearest to the origin is of the maximum order and the value of maximum shear stress along its path is the

Figure 16. Schematic diagram of photoelastic model.

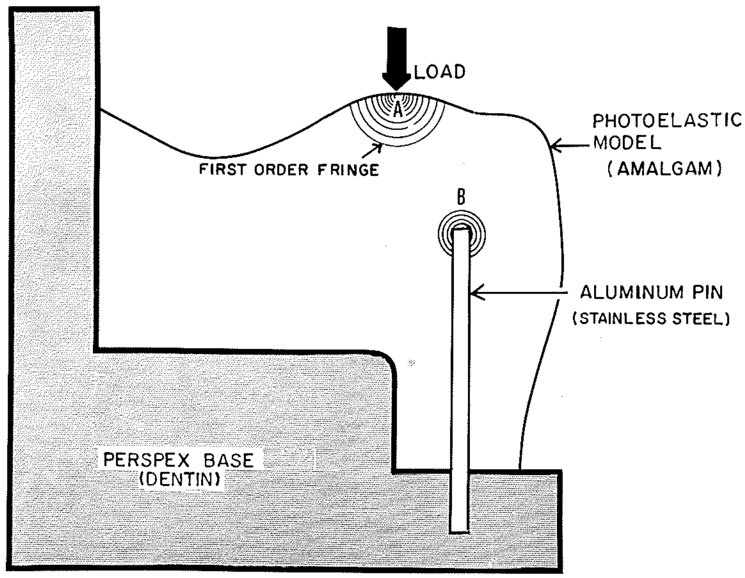
LOAD
A
PHOTOELASTIC
MODEL
(AMALGAM)
FIRST ORDER FRINGE
B
ALUMINUM PIN
(STAINLESS STEEL)
PERSPEX BASE
(DENTIN)

Figure 16

highest for a particular loading condition.

A value for principal stress difference $(\sigma_1 - \sigma_2)$ at any location in the model may be computed by determining the fringe order at that location and employing the formula,

$$(\sigma_1 - \sigma_2) = \frac{fC}{t}$$

where: f is the fringe order,

C is the photoelastic constant of the material,

t is the thickness of the model.

Maximum shear stress τ_{max} may be calculated by utilizing the formula,

$$\tau_{max} = \tfrac{1}{2}(\sigma_1 - \sigma_2).$$

The value of the photoelastic constant, C, is obtained by determining the principal stress difference, $(\sigma_1 - \sigma_2)$ and the fringe order, f, at the center of the disc which is diametrically loaded in compression. The following formulas are employed for this purpose:

$$(\sigma_1 - \sigma_2) = \frac{8P}{\pi D t}$$

where: P is the load,

D is the diameter of the disc,

t is the thickness of the disc.

$$C = \frac{(\sigma_1 - \sigma_2)}{f}$$

where: f is the fringe order at the center.

RESULTS

Part I - Experimental Determination of Axial Stiffness for Retentive Pins in Human Dentin

Mean values of sixty axial deflection measurements for each condition of pin anchorage were calculated. The corrected means were obtained by deducting the following correction factors from the measured means:

1.60 μ for the end effect,

0.50 μ for the canting of the transducer housing,

0.16 μ for the longitudinal deflection of the housing.

The corrected means of axial deflection, axial stiffness values calculated from these and the standard deviations are shown in Table II.

The results of analysis of variance performed for the values of axial deflection are shown in Table III.

The differences in the corrected means of axial deflection values for pins in Conditions 1, 2, 3 and 4 were found to be significant at ninety-nine percent level of confidence. The difference between the corrected means of Conditions 4 and 5 was not significant even at ninety-five percent level of confidence.

Table II

Axial Stiffness of Pins in Dentin

Condition of Pin Anchorage	Corrected Mean Deflection (μ)	Stiffness (Nw/m)	Standard Deviation (μ)
1. Loose-fit	6.9	2.9×10^6	1.2
2. Friction-locked	4.1	4.8×10^6	1.0
3. Cemented	2.8	7.1×10^6	0.4
4. Self-threading	2.4	8.7×10^6	0.5
5. Self-threading-cemented	2.2	9.4×10^6	0.2

Table III

Analysis of Variance

Source of Variance	Degrees of Freedom	Mean Squares
Conditions of Pin-anchorage	4	75.183
Number of Pins	19	0.989
Error	76	0.517
Total	99	

Part II - Two Dimensional Photoelastic Stress Analysis of a Pin Retained Amalgam Restoration

Figures 17 and 18 illustrate isochromatic fringes produced in the control model without a pin, subjected to loading forces of 355 Nw and 710 Nw, respectively.

Isochromatic fringes, produced under similar loading forces in the models simulating four conditions of dentin-pin-amalgam relationship are illustrated in Figures 19 to 26, inclusive. Figures 27 to 30, inclusive, illustrate fringes in these model conditions under nominal loading force of 35 Nw.

Table IV presents the maximum number of fringes produced at two locations in each model under the loading forces of 355 Nw and 710 Nw.

Figure 31 illustrates isochromatic fringes produced in the calibration disc under a loading force of 355 Nw. Values for principal stress difference and the fringe order at the center of the disc, as well as the photoelastic constant of the material, are presented in Table V.

Values of maximum shear stresses, produced at two locations in each model under loading forces of 355 Nw and 710 Nw, are presented in Table VI.

Figure 17. Isochromatics
model condition "a"
no pin
load - 355 Nw.

Figure 18. Isochromatics
model condition "a"
no pin
load - 710 Nw.

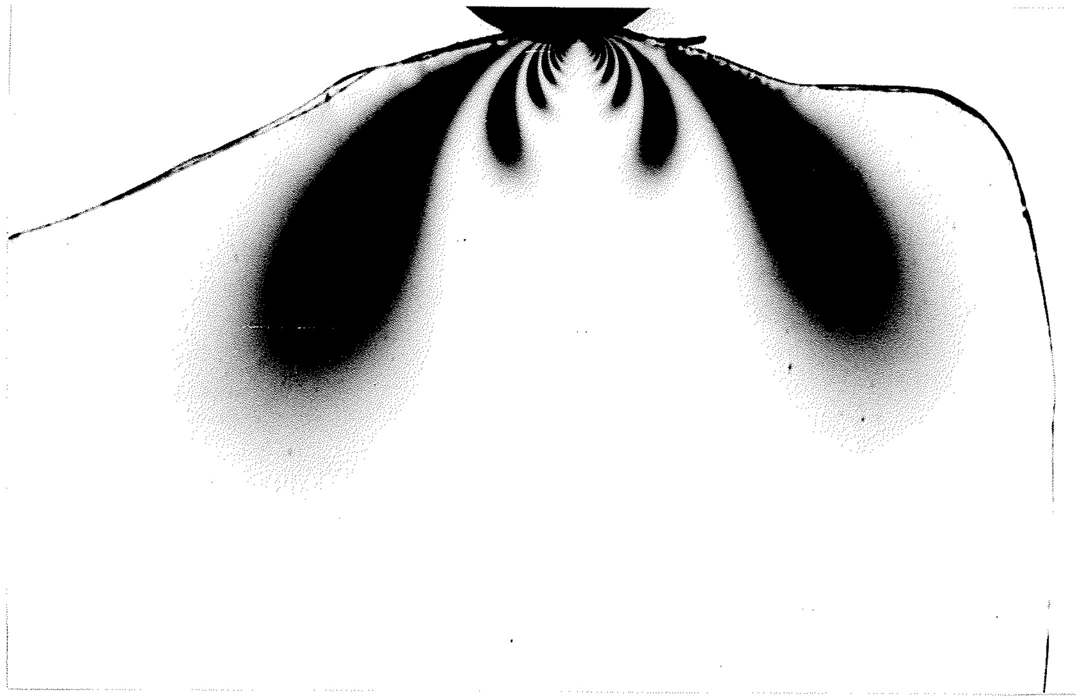

Figure 17

Figure 18

Figure 19. Isochromatics
model condition "b"
low-stiffness-unbonded pin
load - 355 Nw.

Figure 20. Isochromatics
model condition "d"
low-stiffness-bonded pin
load - 355 Nw.

Figure 19

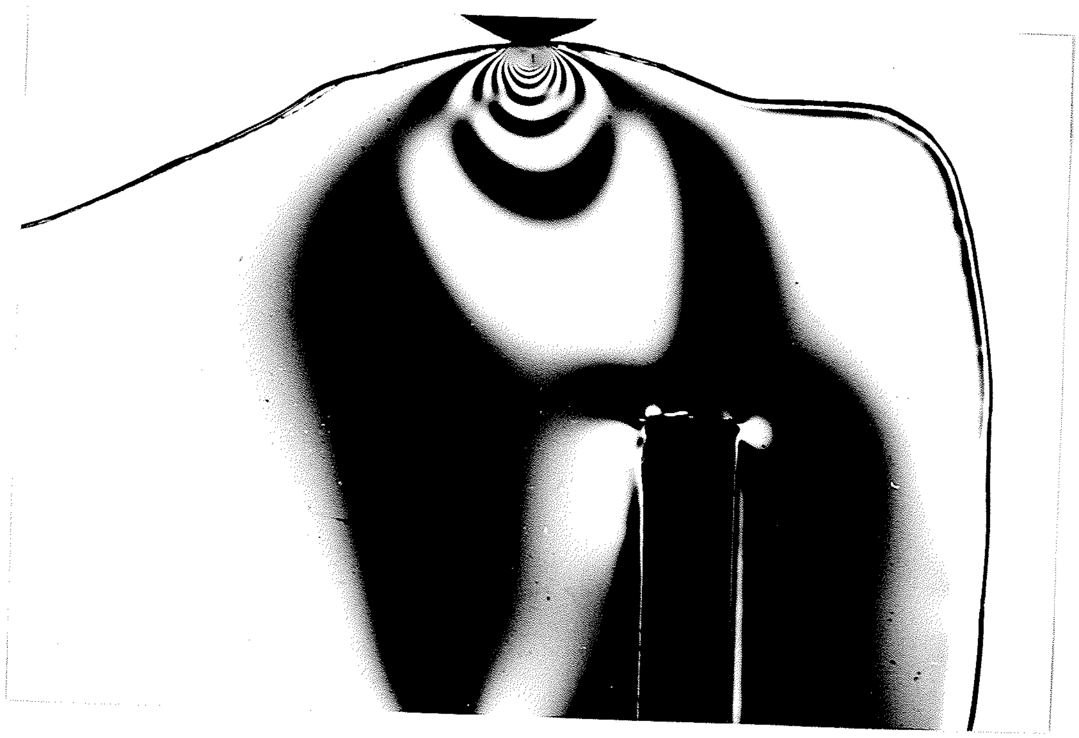

Figure 20

Figure 21. Isochromatics
model condition "c"
high-stiffness-unbonded pin
load - 355 Nw.

Figure 22. Isochromatics
model condition "e"
high-stiffness-bonded pin
load - 355 Nw.

Figure 21

Figure 22

Figure 23. Isochromatics
model condition "b"
low-stiffness-unbonded pin
load - 710 Nw.

Figure 24. Isochromatics
model condition "d"
low-stiffness-bonded pin
load - 710 Nw.

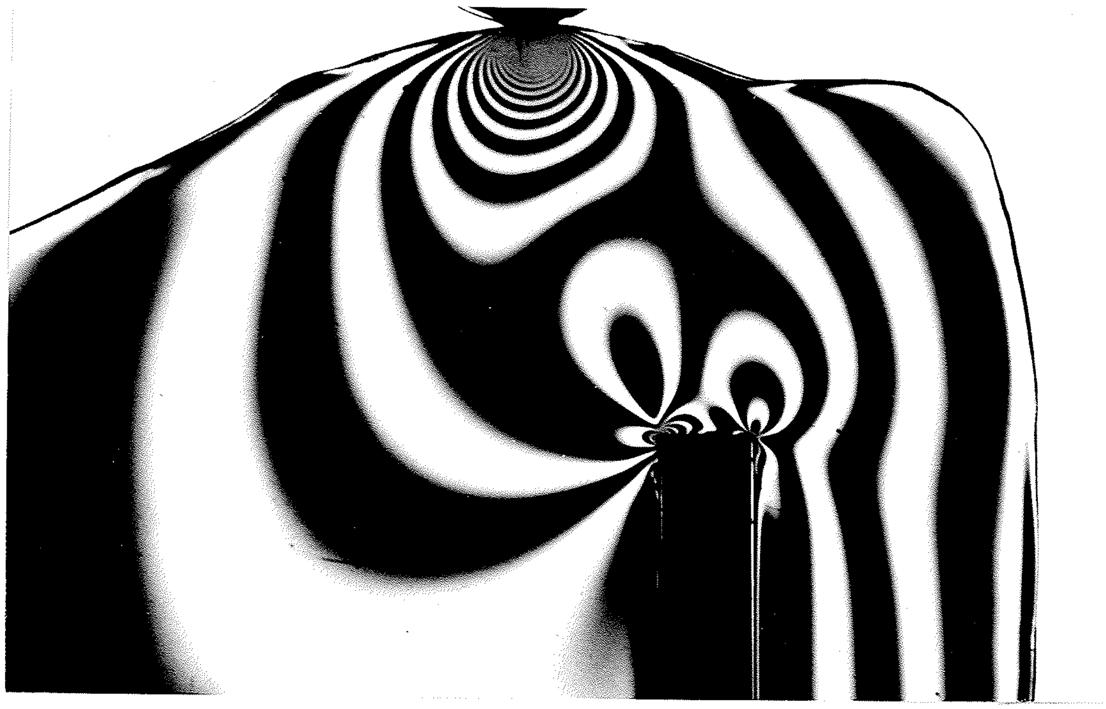

Figure 23

Figure 24

Figure 25. Isochromatics
model condition "c"
high-stiffness-unbonded pin
load - 710 Nw.

Figure 26. Isochromatics
model condition "e"
high-stiffness-bonded pin
load - 710 Nw.

Figure 25

Figure 26

Figure 27. Isochromatics
model condition "b"
low-stiffness-unbonded pin
nominal load - 35 Nw.

Figure 28. Isochromatics
model condition "d"
low-stiffness-bonded pin
nominal load - 35 Nw.

Figure 27

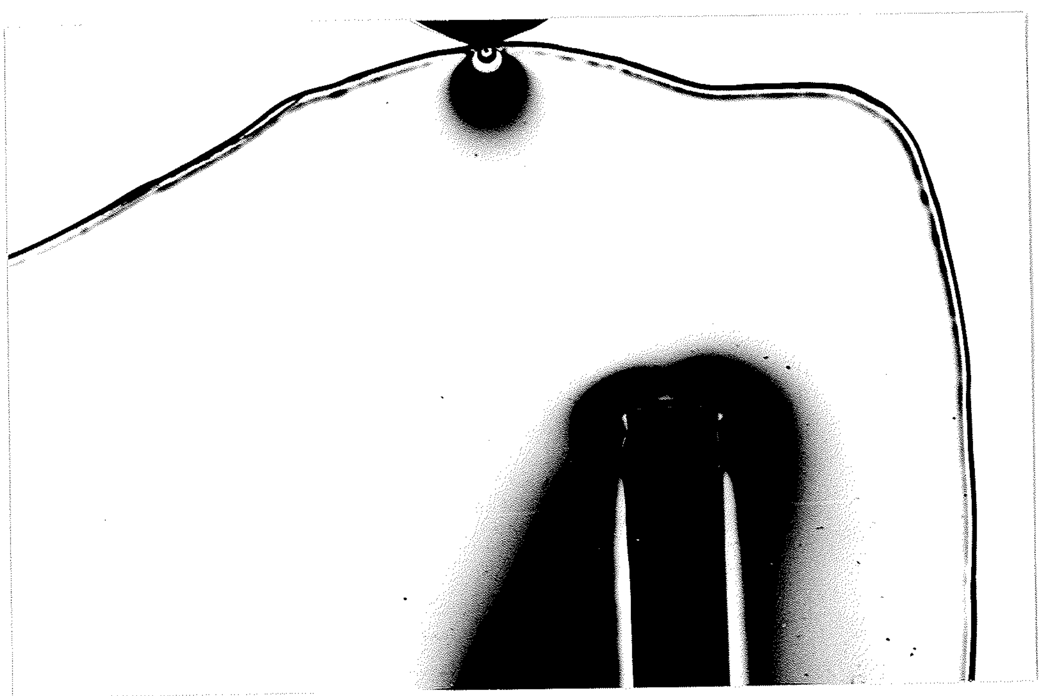

Figure 28

Figure 29. Isochromatics
high-stiffness-unbonded pin
nominal load - 35 Nw.

Figure 30. Isochromatics
model condition "e"
high-stiffness-bonded pin
nominal load - 35 Nw.

Figure 29

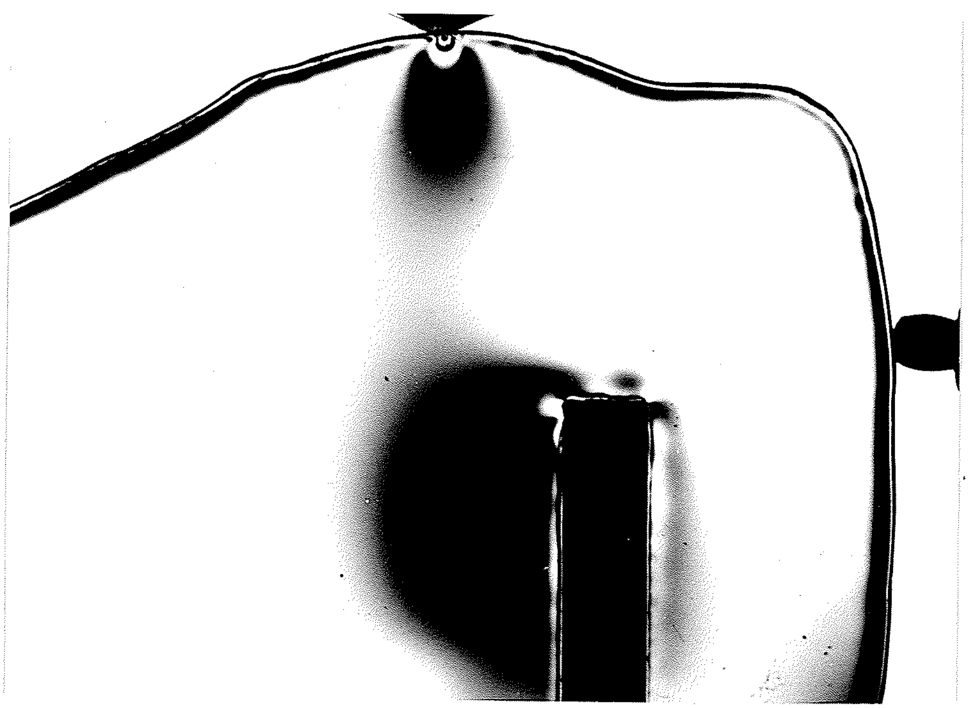

Figure 30

Table IV

Maximum Fringe Orders at Two Locations in Different Models

	Maximum Fringe Order					
		At Top of Pin				
Load Nw	At Point of Load Application	a	b	c	d	e
355	10-12	1.5	3	1	4	1.5
710	17-20	2.5	4	2	6	2.5

(a) Control model - no pin

(b) Low-stiffness-unbonded

(c) Low-stiffness-bonded

(d) High-stiffness-unbonded

(e) High-stiffness-bonded

Figure 31. Isochromatics in calibration disc under diametral compressive load - 355 Nw.

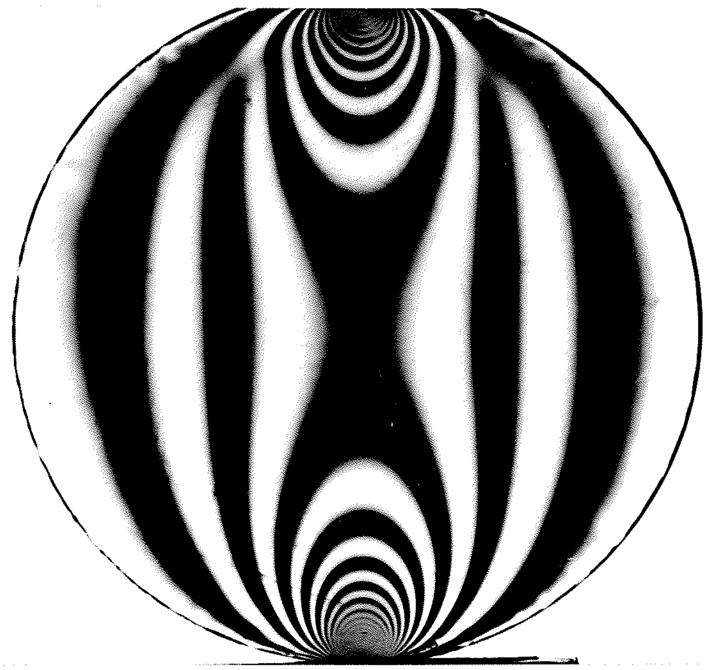

Figure 31

Table V

Calibration

Principal Stress Difference	17×10^5 Nw/m^2
Fringe Order	3.5
Photoelastic Constant	4.9×10^5 Nw/m^2/fringe/meter

Table VI

Values of Maximum Shear Stress

in Different Pin Conditions

Load Nw	At Point of Load Application	Maximum Shear Stress x 10^5 Nw/m^2 At Top of Pin a	b	c	d	e
355	100-115	15	29	10	39	15
710	165-195	24	39	19	58	24

(a) Control model - no pin

(b) Low-stiffness-unbonded

(c) Low-stiffness-bonded

(d) High-stiffness-unbonded

(e) High-stiffness-bonded

The stiffness values are recorded in Table II. Conditions 1 and 5 are representative of theoretically extreme cases for "loose-fit" and "built-in" pins, respectively. The mean stiffness values measured for these pins are close to the calculated values of 1.8×10^6 Nw/m and 10×10^6 Nw/m, respectively. The variability in deflection measurements of pins in Condition 1 is the highest amongst all five conditions. It conforms to the expectation that the nature of support given by the dentin to a pin in an oversized channel would vary greatly according to the amount of contact between the pin and the dentin. For example, it was difficult to remove completely all the debris created by the drilling operation. The debris was responsible for variation in the amount of contact between the pin and the bottom of the channel, from specimen to specimen.

Of the three types of pins used in clinical practice, the friction-locked pins in Condition 2 exhibit the lowest mean stiffness and greatest variability in measurements of deflection. It is reasonable to assume that during the forced insertion of a pin into an undersized channel, the lateral walls of the channel are abraded by minute burs on the end of the pin. Such abrasion reduces the magnitude and uniformity of the lateral support to the pin to an unpredictable degree.

Smooth-cemented pins in Condition 3 yielded a smaller mean stiffness value than self-threading pins in Condition 4. This is to be expected, considering the nature of the mechanical bond in each case. In the case of cemented pins, the amount of stiffness contributed by walls of the channel is dependent upon the degree of mechanical interlocking and coefficient of friction between the cement and the surface of the pin. On an average, the mechanical bond with smooth-cemented pins would be weaker than with self-threading pins. The low variability in deflection measurements obtained for cemented pins can be explained by the fact that the cement displayed consistent adhesive properties and the pins exhibited uniform surface characteristics.

Self-threading pins in Condition 4 did not yield a mean stiffness value as high as that obtained in the case of self-threading-cemented pins in Condition 5. This is probably due to the fact that a self-threading pin is not in intimate contact with the dentin along its entire length. During the process of screwing a pin into the dentin, threads in the dentin at the upper end of the channel are abraded to a greater degree than those at the bottom. Hence, a self-threading pin contacts the dentin at the bottom of the channel more intimately than at the top. In the case of the self-threading-cemented pin, along its entire length, there is a uniform and intimate contact between pin, acrylic polymer and the dentin. Therefore it demonstrates a greater degree of axial stiffness. Because the surface characteristics of threads on metal pins may vary considerably, their abrasive effect on the dentin may likewise be variable. Thus a greater variability in deflection measurements for pins in Condition 4 can be accounted for when compared to those in Condition 5.

The graph illustrated in Figure 31 is typical of deflection tests performed on pins for each condition of anchorage. It demonstrates a satisfactory linearity between the loads and the corresponding deflections, over the range of loading force used in this experiment.

Figure 32. Linear relationship between load and axial deflection of pin.

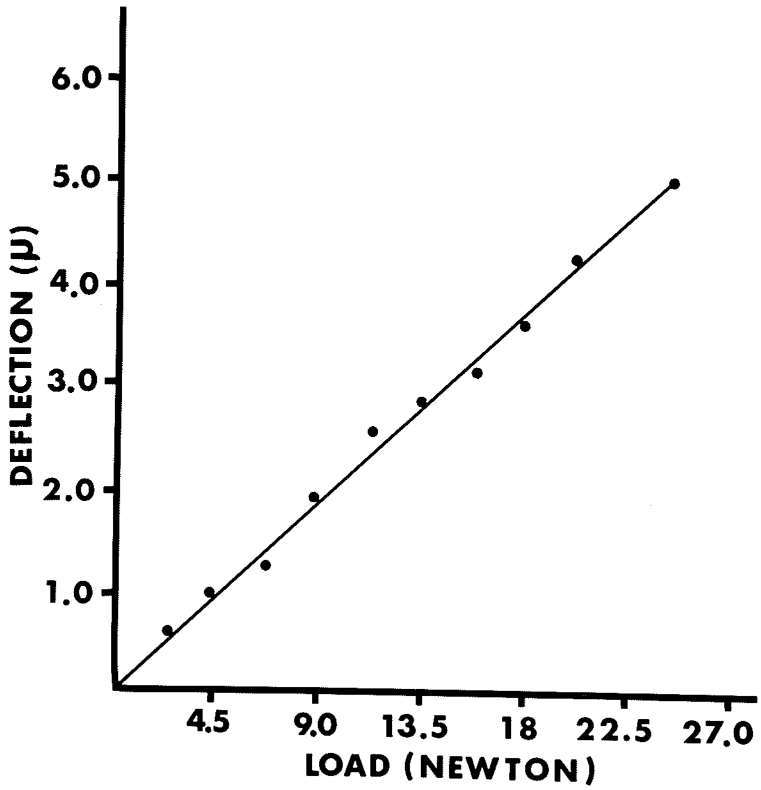

Figure 32

DISCUSSION

The point of application of the load on the occlusal surface, and the area around the top of the pin in the photoelastic model correspond to areas "A" and "B" as illustrated schematically in Figure 16.

The number of isochromatic fringes produced at "A" in all models ranges between 10 and 12 for a 355 Nw loading force and 17 to 20 for a 710 Nw loading force.

The stress-raising effect of the pin is exhibited in all models by isochromatic fringes radiating from the top of the pin. For a given loading condition the stress-raising effect of the pin is related to the number of these fringes. In semi-quantitative terms, the greater the number of isochromatic fringes the greater will be the stress-raising effect of the pin.

The greatest stress-raising effect is exhibited by the high-stiffness-unbonded pin and in descending order is followed by the low-stiffness-unbonded, high-stiffness-bonded and low-stiffness-bonded pins. The same order is evident for both levels of loading.

The stress-raising effect of unbonded pins is approximately three times greater than that of bonded pins.

The stress-raising effect of pins possessing high axial stiffness is one and one-half times greater than that of pins possessing low axial stiffness.

The stress, produced at the top of the pin exhibiting the greatest stress-raising effect, is thirty-three to forty percent of the stress produced at the occlusal surface.

The pin exhibiting the least stress-raising effect produces a stress at its top which is only about eight to ten percent of the stress produced at the occlusal surface.

The difference between the stress concentrations produced by the bonding and the non-bonding type of pins is clearly evident from these results. The hypothesis, forwarded by Duperon and Kasloff[20] that the voids existing between the non-reacting stainless-steel pin and the amalgam matrix act as stress raisers is found to be correct. Such voids would be virtually eliminated in case of electroplated pins, thus reducing the stress concentrations. The reduction in stress concentration is reflected in the higher strength values for amalgam specimens containing electroplated pins, as obtained by the above investigators.

It appears reasonable to apply the results of this investigation to the nature of the bond between the stainless-steel pin and an electroplated layer of silver or gold. The poor quality of such a bond has been shown to produce voids[19]. These voids probably contribute to the increase in stress concentration produced in amalgam specimens containing such pins which, therefore, exhibit decreased strength as compared to specimens without pins[17].

Under the conditions which are simulated in these experiments, failure of the restoration would occur at the occlusal surface before the stress value at the top of the pin approaches the harmful level. In clinical situations, however, conditions may vary and failure could occur as a result of the stress-raising effect of the pin. The condition which is likely to be the most variable is the area over which the occlusal load is distributed. If this area is increased, the stress level at the occlusal surface will be reduced, though, the stress level at the top of the pin will remain unaltered. The relationship between stresses at these locations on the basis of percentage will be drastically changed. Other factors which may increase the stress level at the top of the pin are its geometry and its distance from the point of load application. Sharp jagged tops produce greater stresses than smooth rounded ones. Shorter the distance between the top of the pin and the point of load application, the greater will be the stress concentration produced.

The margin of safety, in terms of stress levels, appears to be adequate in the case of low-stiffness-bonding type of a pin for variable clinical conditions such as above. In the case of high-stiffness-unbonding type of a pin, however, such a margin of safety is significantly reduced. The chances of a failure of a restoration due to stresses procuded by such pins are increased in clinical situations.

The importance of correct simulation of physical relationships between the components of a structure, in the photoelastic model is well illustrated by the results of this investigation. In future photoelastic work, concerning retention pins, it would be desirable to take into account the actual dentin-pin-amalgam relationships in addition to maintaining the relative values for elastic moduli.

A quantitative relationship may exist between stress concentrations and strength properties of pin-amalgam specimens. Similarly, there may be a direct correlation between the metallurgical and mechanical properties of the pin-amalgam bond and the stress concentrations produced. Investigations directed towards these aspects may assist in predicting the effect of pins on the strength of amalgam more accurately.

SUMMARY

Certain aspects of stress distribution in an amalgam restoration influenced by a retentive pin are discussed. It is postulated that the amount of stress concentration produced by a pin is influenced by the axial stiffness of the pin and the nature of the pin-amalgam relationship.

Axial deflection of pins, anchored in specimens of human dentin by five different methods, was measured with a specially constructed apparatus to an accuracy of 0.1 μ. Three of the anchoring methods were similar to those employed in clinical practice. The other two methods represented extreme conditions and were included to check theoretical predictions of deflection measurements. Axial stiffness values for pins were calculated from these measurements.

A two-dimensional photoelastic stress analysis of a model which represented a pin-retained Class II amalgam restoration was undertaken. The model simulated conditions of bonding and non-bonding of the pin to the amalgam and those in which pins possessed properties of low and high axial stiffness. The stress-raising effect of the pin was related to the number of isochromatic fringes produced at the top of the pin. The stress-raising effects of different pin conditions were determined by counting the number of fringes produced. The same technique served to determine the relative difference between stress concentrations produced at the occlusal surface of the restoration and those around the top of the pin.

Statistical analysis of variance indicated that the axial stiffness of pins used in clinical practice varied significantly. The self-threading pin exhibited the greatest axial stiffness, followed by the cemented pin and the friction-locked pin. A pin which bonded with the amalgam as well as one which possessed low axial stiffness, produced less stress concentration than a pin which did not bond with amalgam or did not possess a high degree of axial stiffness. The greatest amount of stress concentration was produced by a very stiff pin which did not bond with the amalgam. Under the conditions described for this investigation, the amount was found to be below a level which could be deleterious to the strength of the restoration. In clinical situations, however, these conditions may vary greatly. As a result, chances of a failure of the restoration due to the stress raising effect of a pin may be significantly increased.

Results demonstrate the validity of the hypothesis that voids between non-reacting stainless-steel pins and amalgam matrix produce additional stress concentrations. Results of the study appear to substantiate the advantages of utilizing surface-reactive electroplated pins which would produce less of a weakening effect upon the amalgam.

CONCLUSIONS

1. Stress concentration produced by a pin in an amalgam restoration is affected by the nature of the bond between the pin and the amalgam as well as the axial stiffness of the pin. The effect of bonding is more pronounced than that of axial stiffness.

2. Axial stiffness of pins in dentin varies significantly due to the different anchoring methods employed. The self-threading pin exhibits the greatest axial stiffness, followed by the cemented pin and the friction-locked pin, with the approximate ratio of 7:6:4.

3. A pin which forms a bond with amalgam produces one-third the amount of stress concentration compared to that of an unbonded pin.

4. A pin which possesses the property of low axial stiffness, produces two-thirds of the amount of stress concentration compared to a pin with high axial stiffness.

5. A pin which does not bond to the amalgam and which exhibits the highest value of axial stiffness produces the highest degree of stress concentration. This amount is at least three times as great as the amount of stress concentration produced by a pin which bonds to the amalgam and which possesses low axial stiffness.

6. Under ideal laboratory conditions, such as those described in this investigation, even the greatest stress concentration produced around the top of the pin would not be high enough to cause failure of the restoration.

7. In clinical situations, factors such as cusp contact area, geometry of the top of the pin and the bulk of amalgam over it are likely to vary, as a result, the failure of a restoration due to the stress raising effect of the pin could occur. The probability of a failure is greater in the case of unbonding type of a pin than in the bonding type.

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