Development and use of photoelasticity laboratory for Montana State College.
by Max A Burroughs

A THESIS Submitted to the Graduate Faculty in partial fulfillment of the requirements for the degree of Master of Science in Civil Engineering at Montana State College

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The design and construction of the apparatus is presented as well as the visual and quantitative distribution of stresses acting at a section. The photoelastic stress results are compared with an analytical solution.

A haunched-girder bant model was used in the investigation.' The results obtained by the two methods mentioned were in close agreement at a section away from stress concentration. However, at a point where stress concentration occurs, the photoelastic solution gave a much larger stress than the analytical solution.

THE DEVELOPMENT AND USE OF A PHOTOELASTICITY LABORATORY FOR MONTANA STATE COLLEGE

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Head, Major Department

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ABSTRACT

The photoelastic approach to model study is presented for an indeterminate structure. The appendix to the thesis briefly contains the theory of light, stress, and photoelasticity that is involved in the solution of the problem.

The design and construction of the apparatus is presented as well as the visual and quantitative distribution of stresses acting at a section. The photoelastic stress results are compared with an analytical solution.

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INTRODUCTION

Purpose

The purpose of this thesis is to solve a statically indeterminate stress problem by photoelasticity. The experimental results are compared with an analytical solution. Before the photoelasticity solution could be made, it was necessary to design and construct a suitable apparatus.

The development of a permanent accurate apparatus with a substantial saving in money has been attempted.

It is hoped that the photoelastic apparatus will permit engineering students at Montana State College to obtain an introduction to photoelastic analysis. Senior and graduate students may also use the apparatus for specialized study.

Importance

Examples of design problems which are beyond the scope of the analytic methods the designer has at his disposal are numerous. Throughout the airplane structure many members are indeterminate to several degrees, thereby making an exact solution impractical. The mathematical theory of elasticity also becomes highly difficult and tedious when boundaries and loads become irregular. Stress concentrations originate at sharp discontinuities such as fillets, holes, grooves, and small irregularities on the surface. Failure at any point in the structure or machine may ultimately cause complete failure. The true value of the stress concentrations may be of such importance that it must be accurately determined.

The use of photoelasticity makes possible the solution of extremely complicated problems that cannot be reasonably approached by any mathematical solution. Experiments also show that actual stress distribution is not always as computed by the theory of elasticity. This is due to assumptions that must be made concerning the application of external loads and the behavior of internal strain. Therefore, the economical and exact method of photoelasticity may be turned to for a more complete understanding of the internal stress conditions. By photoelastic studies, a visual as well as a quantitative solution can be made.

Previous Work

There have been stress investigations made by photoelasticity for a considerable length of time. Professor E. G. Coker and L. N. Filon of the University of London[1] introduced photoelasticity to the engineering profession. They began their work about 1900.

The solution of problems by photoelasticity has been advanced to the point that many laboratories are supported by grants from various industrial concerns. Refinement of model material has brought forth a resin that yields extremely accurate results. This resin is called Bakelite and its commercial numbering is BT-61-893. Early experiments used models of glass, celluloid, or gelatin.

One of the foremost American engineers today in the photoelasticity

1. Coker, E. G., and Filon, L. N. 1930 TREATISE ON PHOTOELASTICITY, Cambridge Press, London.

field is Dr. Max Mark Frocht[2,3]. The two books by Dr. Frocht provide an excellent background in the field.

APPARATUS DESIGN

The general arrangement of the apparatus is somewhat uniform in all laboratories. An understanding of the apparatus design requires a knowledge of photoelastic theory, and a brief synopsis of the theory will be presented here. Appendix A presents a more thorough explanation.

Behavior of Light

The most simple arrangement is called the plane setup and is shown in Fig. A-5. A light wave coming from a light source is passed through a polaroid lense. The polaroid lense allows only waves vibrating in one plane to continue. This wave next encounters the loaded model. The model material has the property of splitting the wave into two waves, each vibrating parallel to one of the principal stress directions. These two waves next encounter the second polaroid lense and again are converted into a single wave vibrating in one plane.

The plane setup shows the stress lines in the loaded model and also will be used to obtain the isoclinic lines. The purpose of isoclinic lines is explained later.

For an evaluation of the magnitude of the stresses existing in the model, the apparatus requires refinement. The light source is filtered to allow for the passage of waves of one color only, since the length of

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2. Frocht, M. M. 1941 PHOTOELASTICITY, Vol. 1, John Wiley & Sons, Inc., New York.
3. Frocht, M. M. 1946 PHOTOELASTICITY, Vol. 2, John Wiley & Sons, Inc., New York.

the light wave is used in the stress-optic relationship. In addition, a quarter-wave plate is placed on each side of the stressed model. The quarter-wave plates retard the wave after it has passed through the polaroid lens by ¼ wave. (See Fig. A-4) Such light is referred to as circularly polarized. The stress pattern only is shown by a circularly polarized setup.

With the two setups mentioned, a visual and quantitative solution can be made.

Lens and Light Source

A light source manufactured for photoelastic purposes was purchased at a cost of $450[4]. This source (see Fig. 1) consists of a mercury light illuminator, filter for 5461 Å, condensing lens, and collimating lens. The light emitted is green and is parallel to the longitudinal axis of the lenses. The diameter of the light field is 8½ inches. Polaroid and quarter-wave plates were also purchased at a total cost of $34. These four plates were also 8½ inches in diameter.

Mount Design

The design and construction of a suitable mount for the purchased equipment was necessary. The commercial metal mount costs approximately $450. It was decided a wooden mount could be substituted without any great loss in accuracy. The total cost of the wooden mount was $20. Fig. 2 gives the necessary data for the mount construction. Select grade oak was used throughout, with the exception of the lens frames and they

4. THE POLARIZING INSTRUMENT COMPANY, 630 Fifth Avenue, New York

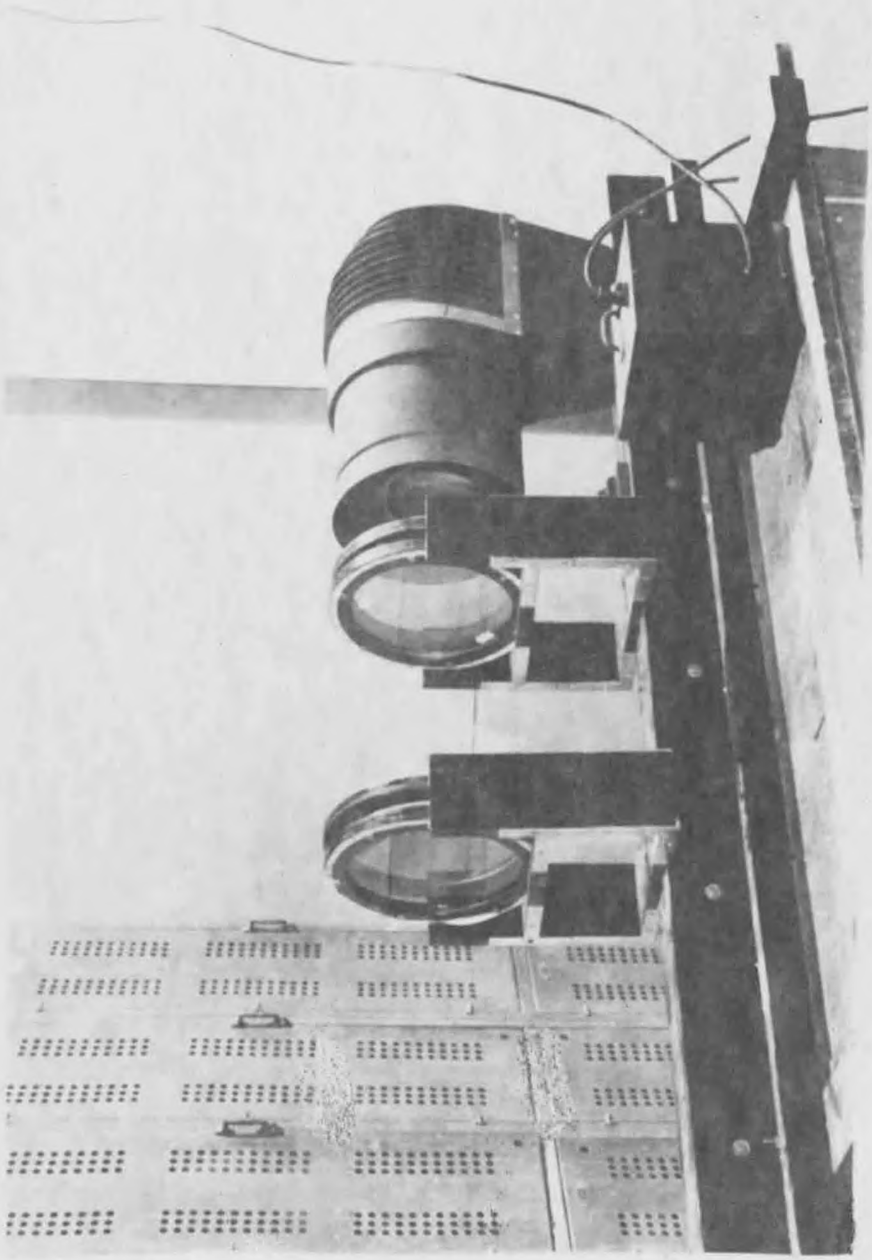
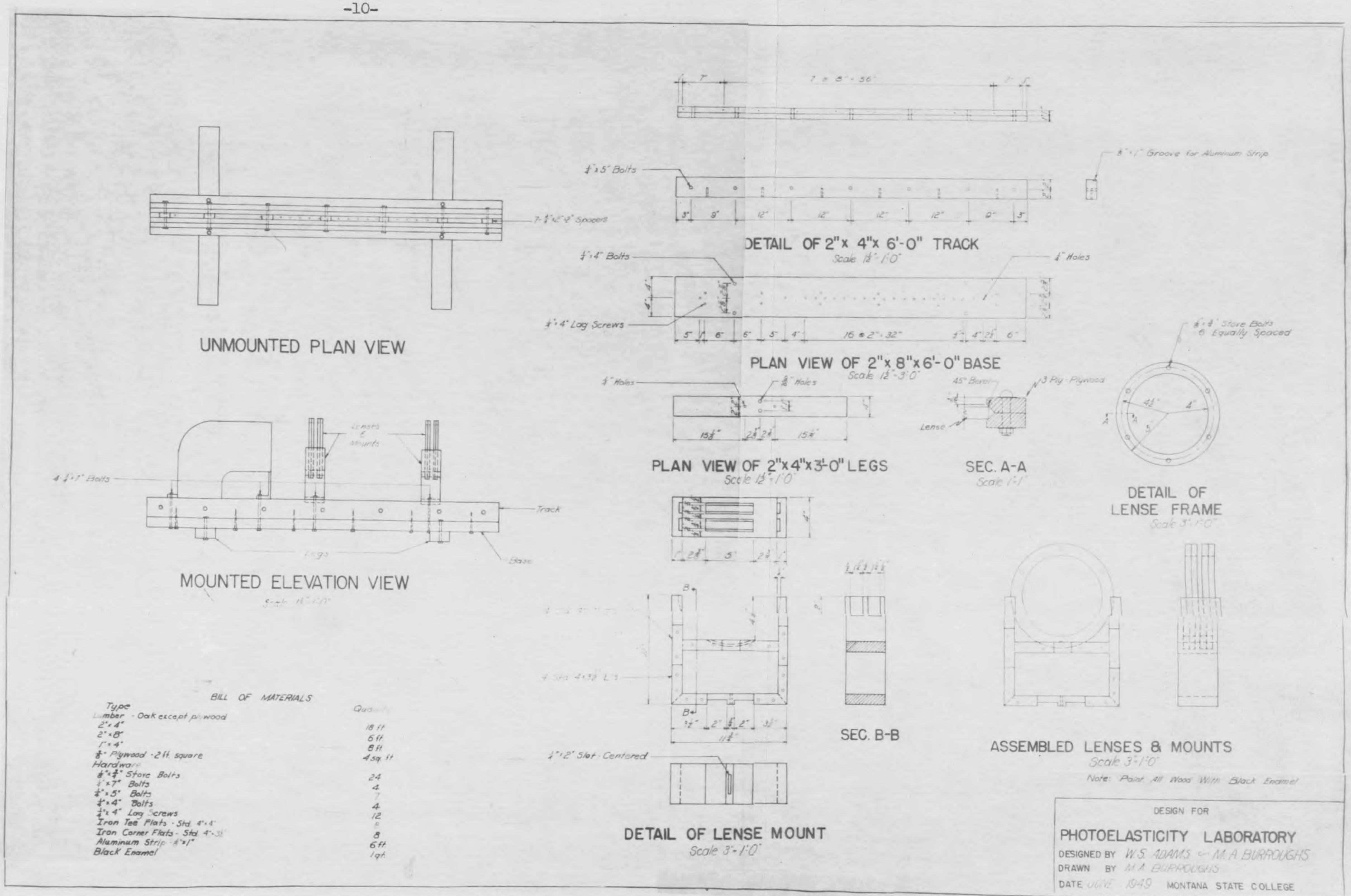


Fig. 1 Assembled Photoelastic Apparatus



BILL OF MATERIALS

Type	Quantity
Lumber - Oak except plywood	
2"x4"	18 ft
2"x8"	6 ft
1"x4"	8 ft
⅜" Plywood - 2 ft. square	4 sq. ft
Hardware	
⅛"x¾" Stove Bolts	24
¼"x7" Bolts	4
¼"x5" Bolts	7
¼"x4" Bolts	4
¼"x4" Log Screws	12
Iron Tee Flats - Std. 4"x4"	[illegible]
Iron Corner Flats - Std. 4"x3½"	8
Aluminum Strip - ⅛"x1"	6 ft
Black Enamel	1 qt.

Fig. 2

were built from 3/8 inch plywood. Fig. 1 is a photograph of the completed apparatus.

PROPERTIES AND PREPARATION OF MODEL

Photoelasticity resin, commonly called Bakelite, was used for the model. Three sheets, approximately 6 in. x 11 in. x $\frac{1}{4}$ in., were obtained for $14.50 per sheet. The commercial numbering of the resin is BT-61-893[5].

Properties

According to Frocht[6], the following properties are necessary for an ideal photoelastic material:

(a) The material must be transparent.

(b) It must be easily machinable to prevent excess building costs.

(c) The optical sensitivity must be high so stress lines may be counted easily.

(d) It must have the proper hardness -- not too brittle to cause machining difficulties but of sufficient hardness so that clamping during machining or other operations will not cause distortion or permanent stresses.

(e) There must be an absence of undue optical or mechanical creep.

(f) There must be freedom of initial stresses.

(g) The material must be isotropic.

5. Ibid.
6. Frocht, M. M. 1941 op. cit., p. 323.

(h) Linear stress-strain and linear stress-fringe relations must exist.

(i) The material must have a high enough modulus of elasticity so that the models suffer small deformations only and the shape stays essentially constant.

(j) There must be a constancy of properties during moderate changes in temperature and treatment.

(k) The cost of the material must be moderate.

Bakelite is one of the most ideal materials with which to work at present. Frocht[7] presents the following physical properties of Bakelite: Its linear-stress relation holds till 6000 psi., and its stress-fringe relation holds to 7000 psi. The modulus of elasticity is about 615,000 psi. The tensile strength is 17,000 psi. for a five minute loading. Poisson's ratio is 0.365.

Preparation

Frocht[8] gives the following chronological rules for building a model:

(a) Trim the sealed or cast edges of the plate and anneal if necessary. This necessity will be revealed by inspection in the polariscope.

(b) Store the annealed material for several months or years before using. Time seems to relieve some of the initial stresses.

7. Ibid., p. 326.
8. Ibid., p. 360.

(c) Cut a piece of material, a blank, slightly larger than that necessary for the overall dimensions of the model.

(d) Turn or mill the face of this blank to within 0.020 in. of the desired thickness.

(e) Examine this blank in the polariscope, using oil to increase the transparency. Additional annealing, if required by the material, should be done at this stage.

(f) Grind the blank to the desired thickness.

(g) Rough Polish with felt cloth and jewelers rouge.

(h) Lay out the shape of the model on the roughly polished blank.

(i) Cut with a scroll or saw to 1/16 in. of the true dimensions, and machine with an end mill or file to within 0.030 in. of the shape.

(j) Give the model its final polish with a washed and rinsed Selvyt Cloth.

(k) Carefully machine the polished model to its final dimensions.

(l) Make investigation or take loaded model pictures immediately after step k is completed.

The Bakelite sheet in its original shape was put between the crossed polaroid lenses to determine the condition of initial stress. There were severe edge stress conditions extending about $\frac{1}{4}$ in. into the plate. These original stresses were apparently set up when the sheet was molded.

The edge stresses were removed by trimming the ¼ in. off with a coping saw. This operation did not set up any permanent stresses as the temperature of the material was not changed a large amount.

The faint stress lines existing in the plate proper were removed by annealing. This process consisted of placing the material on a solid smooth glass surface and placing it within an oven. By slowly changing the heat from 0 to 250 and back to 0 degrees, the internal stresses were removed. The process took four cycles to remove all the internal stresses, each cycle requiring about 12 hours.

As suggested by Frocht, nonuniformity in thickness would disperse light and cause a blurred stress pattern. The sheets were not of uniform thickness and were ground to a thickness +0.020 in.[9] Unless a laboratory has a machine reserved for plastic work only, it is very difficult to approach the required limitation by milling.

For this experiment a surface grinder was used to obtain the required uniform thickness. The final thickness varied ±0.005 in. The only grinder available held all stock in place by a magnetic field. The nonmagnetic Bakelite sheet required some additional attachments to hold it.

Metal clips were shaped to fit the ends of the plate and contact the magnetic field. It was, however, impossible to develop sufficient contact area due to the limited size of the magnetic table and this method was abandoned.

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9. Ibid., p. 361.

The next and most successful attempt resulted in gluing the Bakelite to a cast iron block. Lepage's glue was used. It was quite difficult to obtain enough bond between the cast iron and the Bakelite with the glue. This step in the model construction should be investigated further.

The sheet was hand polished until all scratches produced by the surface grinder were removed. Emery cloth of grades 240, 320, and 600 gave a final surface clear of all but the very minute marks. Crocus cloth of grade NHB was first tried but it was not hard enough to remove the scratches. Garnet paper, wet or dry, of grades 2/0 and 4/0 did not successfully remove the marks as it too was not hard enough.

The model was cut out of the sheet $\frac{1}{4}$ in. larger than true size. The oversize dimension was precaution against chipping or other injury to the model. See Fig. 4 for the finished model.

From the rough model the exact size was achieved by hand filing. The filing operation took considerable time but the finished model had edges nearly perpendicular to the faces and a stress-free condition.

Final polishing of the model by Selvyt cloth and jewelers rouge was attempted by hand without satisfactory results. The success of this step calls for a firm polishing wheel. This operation, when completed, eliminates all scratches.

The model (Fig. 4) had pin end conditions. The diameters of the holes for the pins were 0.1875 in. The final diameter was obtained by starting with a 1/16 in. drilled hole and increasing it by 1/32 in. increments. This gradual enlargement of the hole was precaution against chipping.

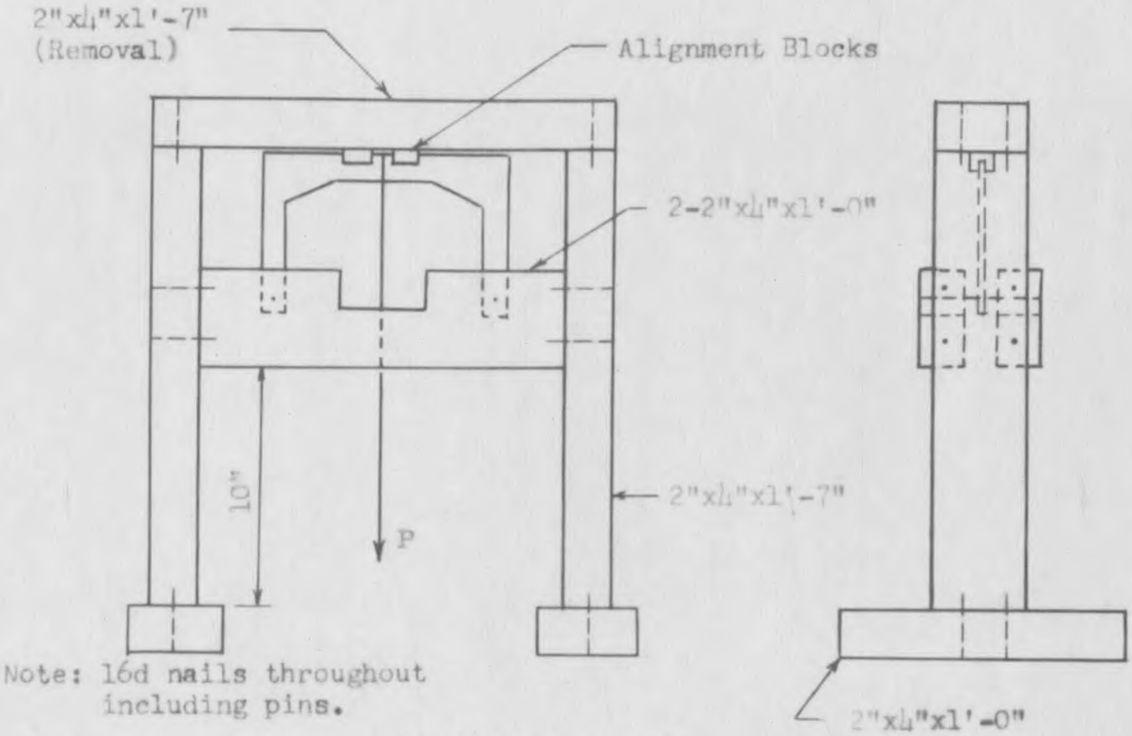

Fig. 3 Loading Frame
Scale: $1\frac{1}{2}$"=1'-0"

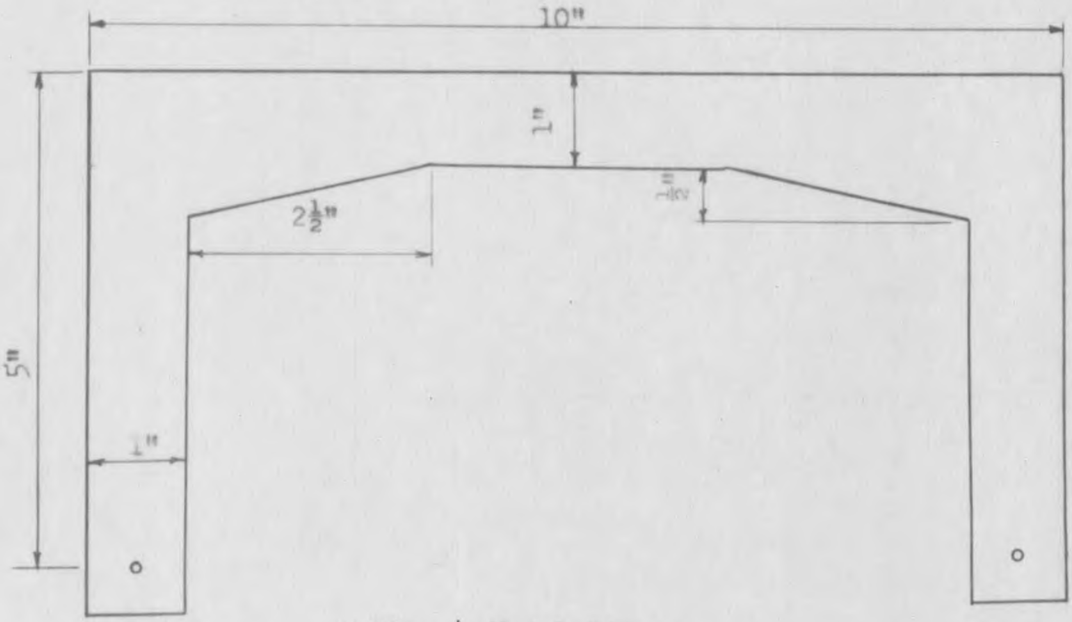

Fig. 4 Model Digram
Scale: $\frac{1}{2}$"=1"

The pins used were 6d nails. A wire and turnbuckle was attached to the columns at each pin to prevent horizontal movement that might result from imperfection in the pin-hole fitting.

Mounting and Loading the Model

A loading frame was constructed for the model as shown in Fig. 3. The frame was built sufficiently rigid to prevent appreciable deflection.

The load consisting of a weighted bucket was applied at the centerline of the model by a wire loop. The total weight applied to the model was 58 lb. This weight gave a clear stress pattern and did not pass the allowable stress-fringe relationship.

Photographing the Loaded Model

A $2\frac{1}{4}$ by $3\frac{1}{4}$ in. Eastman Recomar camera was used in taking the pictures. (Figs. 5-15). Super XX Kodak film with an exposure time of $1\frac{1}{2}$ minutes and an f-16 opening gave good results. The only light coming into the camera was that passing the second polaroid lens.

It is not necessary to go to the expense of making photographs. A 5 by 7 in. camera may be set up and the image on the frosted glass traced. This method is as accurate as the one used in this paper. A large saving in time would also result in the tracing process.

PHOTOELASTIC STRESS EVALUATION OF MODEL

For a more complete development of the theory and explanation of photoelastic analysis, the reader is referred to Appendix A, B, and C or references 2 and 3. The following presents only the method of analysis used.