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EFFECT OF STRESS CONCENTRATIONS IN COMPOSITE STRUCTURES

by

C.D. Babcock and W.G. Knauss
Graduate Aeronautical Laboratories
California Institute of Technology
Pasadena, CA 91125

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1. INTRODUCTION

Two projects are being carried out under this grant with the goal of achieving a better understanding of the failure of complex composite structure. This type of structure requires a thorough understanding of the behavior under load both on a macro and micro scale if failure mechanisms are to be understood. The two problems being studied are the failure at a panel/stiffener interface and a generic problem of failure at a stress concentration. This work is described in the following sections.

2. PANEL/STIFFENER FAILURE

Efficient use of graphite epoxy material in aircraft structures requires that stiffened panel components be designed to perform in the post buckled range. The problems associated with this type of design have been effectively resolved over a period of years for aluminum structures. This process involved large numbers of tests on stiffened panels and the development of numerous semi-empirical design rules. The same type of design problems exist for graphite epoxy structure but appear to be accentuated by the unforgiving nature of the material. One problem, the peeling off of stiffeners, is addressed in this report.

Stiffened panels constructed of graphite epoxy are fabricated either by a cocuring process or by postbonding. In cocuring, the panel and the stiffeners are laid up at the same time and then cured together. In postbonding, the panel and stiffeners are laid up and cured separately and then bonded together. It has been observed in either case that the stiffeners tend to separate from the panel when the panel is loaded deep into the postbuckled range. This type of failure rather than panel or stiffener failure seems to predominate at ultimate load.

2.1 Problem Formulation

In order to understand the stiffener-panel separation process it is necessary to examine the postbuckling problem. This type of analysis has been looked at for isotropic plates using either a classical Galerkin type of analysis or numerically using finite element techniques. The classical analyses were usually performed with an interest in the panel deflections or stresses and used idealized boundary conditions.

This allows no interaction between panel and stiffener. Finite element analyses usually were carried out to demonstrate the nonlinear capability of the element or analysis and provide no useful information. It is interesting to note that the well established idea of effective width or methods of determining ultimate load have never been subjected to the scrutiny of a rigorous finite element analysis.

In recent years there has been some effort to examine the post buckling problem for composite structures (ref. 1-9). In some cases the boundary conditions have been idealized as before, in others the interaction of the stiffener and panel has been considered but these are still in the development stage.

All of these analysis treat the panel using plate assumptions and the stiffener is usually treated as a beam. In some cases the stiffener is handled using plate type assumptions (i.e. the section can distort). In either case, these types of analyses must be considered as far field in nature in that they can give results that are valid away from the actual panel/stiffener joint. From a plate standpoint, what is predicted are the bending moments, inplane stress resultants (extensional and shear) as well as Kirchoff type transverse shear. The conversion of these forces and moments into the three-dimensional stress field at a typical discontinuity is a very complex problem. Figure 1 shows in pictorical form what this process might involve. Unfortunately, the details of the conversion would be heavily dependent upon the model idealization. A sharp discontinuity as drawn would lead to a singular stress field at the re-entrant corner. Other complexities such as through-the-thickness stresses at free edges also enter the picture.

Failure of the stiffener/panel intersection will most likely initate at the step in thickness. The local stresses in turn will be dependent upon the details of this joint. However, the relation between the micro (local) stresses and the macro (plate force and moment resultants) stress will be the same for a given joint configuration. Therefore the details of this very complex problem can be circumvented temporarily by fixing the configuration. This will not allow an ultimate resolution of the failure conditions but will permit the problem to be attacked in two stages.

The two stages of such a problem are as follows. First the failure condition for the stiffener/panel intersection is characterized in terms of the macro stresses. This can be done in a simulation test and does not require that a complete panel be tested into the post buckled range. The second stage is relating the macro failure condition to the micro stresses. This is a very complex problem which will not be addressed at this time.

The macro stresses of concern are shown in Figure 1. These consist of the bending moment, transverse shear and two inplane stress resultants. The inplane shear is a difficult force to apply and will not be treated at the present time. The other forces and moments can be examined by a simple beam type test and these tests will be discussed in the next section.

2.2 Macro Failure Condition

For these tests a simulated stiffener/panel joint was used. The configuration is shown in Figure 2. The specimens were provided by NASA Langley. The test specimens were cut from the same panel, therefore, they have nominally the same details at the joint. A close up of this joint on an actual specimen is shown in Figure 3.

For the simulation test it is necessary to determine the relation between the inplane force, N, transverse shear, V, and bending moment, M, that lead to failure. In order for the test to be one that relates to the macro stresses, the loads must be introduced into the structure so that the natural diffusion from macro to micro stresses can occur. It was felt that if the macro stresses were applied at least ten thicknesses away from the joint, then this condition could be satisfied. Based upon a lamina thickness, this becomes greater than 50 thicknesses.

2.3 Inplane Force

The first tests were carried out to determine the influence of the inplane force (normal). Preliminary considerations led to the hypothesis that this force would not be important in the failure condition. In order to substantiate this, the inplane load was applied to the specimen in the normal fashion by pulling the simulated joint in testing machine. Some difficulty was encountered in gripping the specimen at high loads. This problem was overcome by bonding aluminum pieces to the ends of the specimen for gripping. Failure of the specimen was achieved but at such a high stress level that it was deemed to be outside the range of interest. The macro stress at failure was 110,000 psi. The failure occurred in the vicinity of the joint but no joint separation was detected prior to a failure of the specimen. Figure 4 shows one of the failed specimens.

2.4 Bending/Shear Interaction

The bending moment/shear interaction was found using a cantilever beam configuration. The shear load was applied at different distances from the joint and increased until failure occurred. The deflection of the beam was quite large so that calculation of the forces and moments at the joint necessitated consideration of the beam deflection at failure. This was accomplished by tracking the beam configuration during loading using the device shown in Figure 5. By marking the location of the loading rod, the direction and location of the force could be found.

The loading was applied using a standard testing machine which was calibrated and checked for the cross axis sensitivity that this loading techniques introduces. The attachment at the beam was designed so that the force was applied near the center of the beam and no moment was introduced. The details of this fixture are shown in Figure 6.

Figure 7 shows the types of failure that occurred during the tests. No specific differences could be detected over the range of load conditions. Failure usually occurred at the reentrant corners with separation between the first plies of the stiffener and the panel. A few failures pulled up several plies of either the stiffener or the panel. Repeatibility of the failure condition was judged to be plus or minus 10%.

The results of this interaction test are shown in Figure 8 which shows that the failure condition is dominated by the bending moment over the range tested. Higher values of the shear could not be evaluated since the lever arm (distance to the joint) becomes too small for the basic assumption of the test. The highest shear datum point has a lever arm of 1/2 inch which is only 7 thicknesses and somewhat smaller than the 10 thicknesses desired.

3. FAILURE AT A STRESS CONCENTRATION

The advantages to be gained in using composite structures in the aerospace and associated industries cannot be overemphasized. The increasing use of these structures as well as their application in extremely weight-critical designs poses the problem of failure characterization and prediction. The purpose of the present investigation is to study the failure of composite laminated structures in regions of high stress gradient (stress concentrations and to develop progressive fracture models based on experimental observations.

Holes and cut-outs are present in practically all engineering structures and are thus common features that produce stress concentrations. Because of their common occurrence a thorough understanding of their effect under various inplane and out-of-plane deformations is important. Specifically, it is important to understand the effect of stress gradients on the initiation of the damage process as well as its progression. It is this latter effect that we are attempting to ellucidate.

The first phase of the work was reported in Refs. 10 and 11. The work was carried out in two parts. A preliminary investigation was carried out on specimens which were rectangular plates of Graphite/Epoxy T300/5208, the dimensions of which are given in Figure 9. A central circular hole is drilled in the plates to produce the stress concentration effect under inplane loading, applied by a table top compression device. Strain gages are attached to the specimen at selected locations.

Some difficulty was encountered in maintaining a bending free configuration, which problem was overcome by attaching edge supports against buckling but which left the edges of the specimen free to slide. Several specimens tested to failure exhibited a similar failure pattern. Inspection of the strain gage data (in particular the gages attached to monitor through-thickness strains) indicated a nonlinear behavior above a certain applied loading, indicating the probable formation of cracks between laminae. Failure of the plates occurred without any prior indication from the edge of the hole. The failure initiated at a point 90^{o} from the loading direction and the failure spread across the plate i.e. normal to the load line (Figure 10). It was noticed that the initially circular hole was distorted roughly to an oval shape. Strain gauge data obtained from these tests are presented in Figures 11 and 12.

3.1 Holographic Tests

In order to carry out measurements using holographic interferometry it is necessary to isolate the test specimen and loading device against vibration. Together with the optical components these were arranged on a 5x7 foot optical table with pneumatic vibration isolation. All optical components were rigidly attached to the table using magnetic bases.

The basic arrangement used to generate the interferograms is shown in Figure 13. The standard I5mW spectra-physics He-Ne laser operating at 632.8 nm was used as the generating source. A variable beam splitter enables controlling the intensities of the object and reference beams. These beams of equal path length are made to interfere at the position of the holographic plate. Agfa-Gaevert 10E-75 (holographic) plates were used throughout for double exposure holography. The total exposure time depends on he relative intensities of the reference and object beams. The exposed plates were developed in Kodak D 19 developer treated in a Kodak stop bath and fixed using Kodak rapid fixer. The quality of the hologram depends on the various periods of time used in the developing process. The holograms were obtained with a Nikon F camera with a 105 mm f/4 lens. The test specimens were sprayed with flat white primer to obtain a diffusely reflecting surface.

To date we have obtained holograms, a typical one of which is shown in Figure 14. Inasmuch as we are interested in recording out-of-plane deformations in the stress concentration it would be beneficial if no other out-of-plane deformations were present. However, it is evident from the holograms that the specimen undergoes rotation under load in the region of interest. This rotation produces figures that are likely to obscure the phenomenon to be studied. We are presently attempting to trace the source of the rotation, yet expect that it is due to the motion of the composite plate under load, and is, in part, due to the inhomogeneous nature of the material studied. Without doubt, the support conditions which are difficult to improve upon, contribute to this problem.

A next step in improving the holographic recording is to obtain holograms under very small load increments and to observe what happens at one load level before one proceeds to the next. One problem with that approach is, at present, that developing between load increments is so long that the failure process continues while no recording is performed. We are presently exploring ways to achieve this goal, for it seems to us instrumental in following the damage process in a quantitative way. level before one proceeds to the next. One problem with that approach is, at present, that developing between load increments is so long that the failure process continues while no recording is performed. We are presently exploring ways to achieve this goal, for it seems to us instrumental in following the damage process in a quantitative way.

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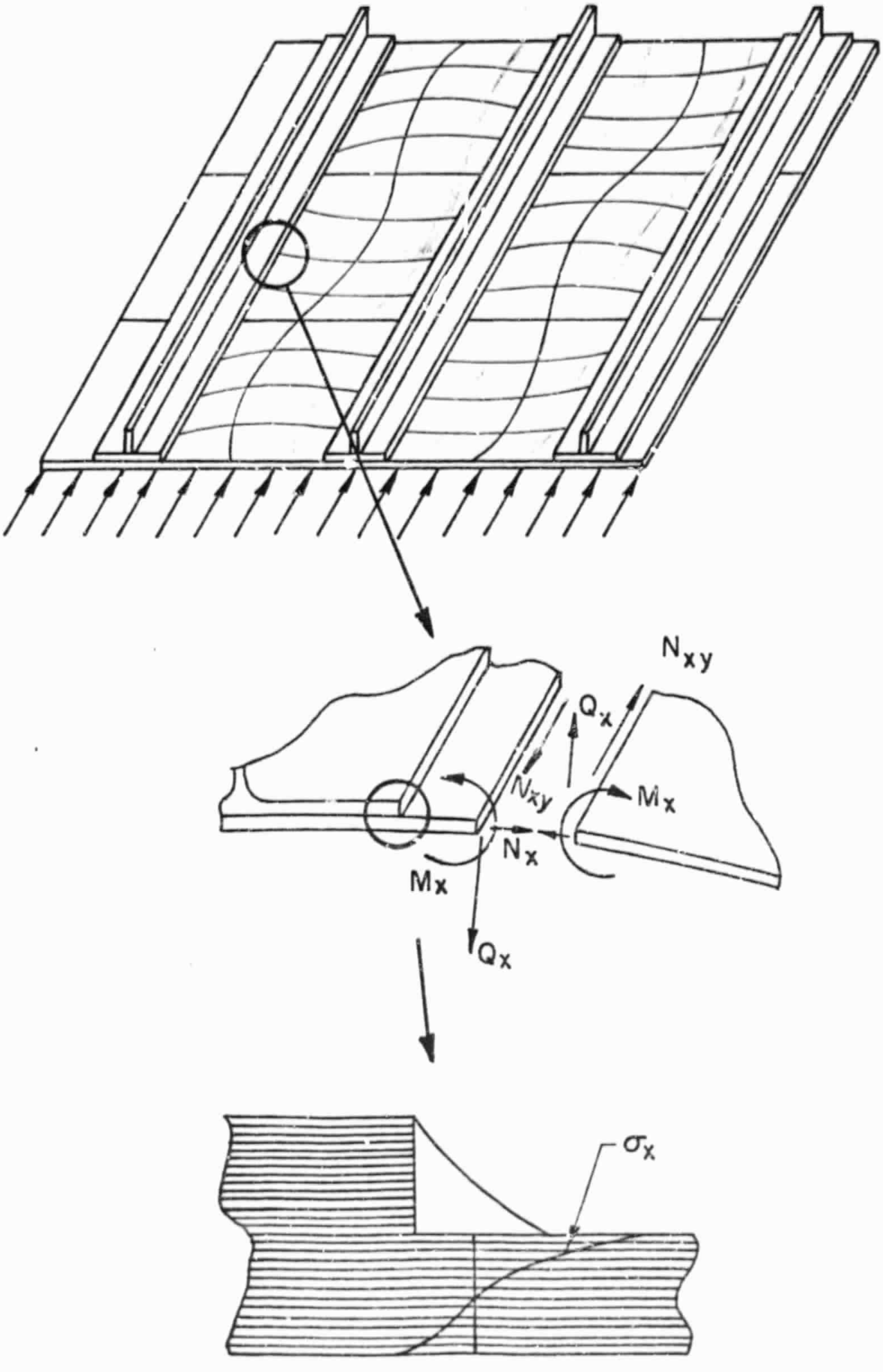

Figure 1. Macro and Micro Stress Fields at Typical Joint

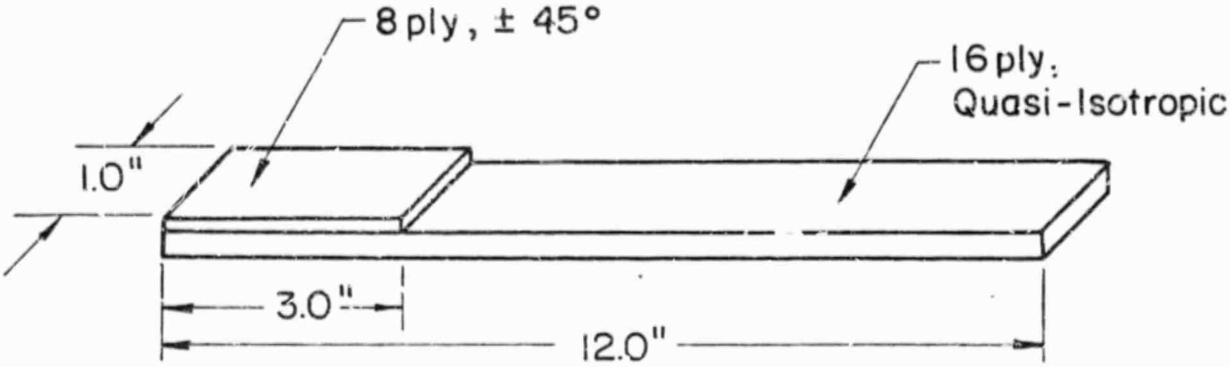

Figure 2. Stiffener Delamination Test Specimen

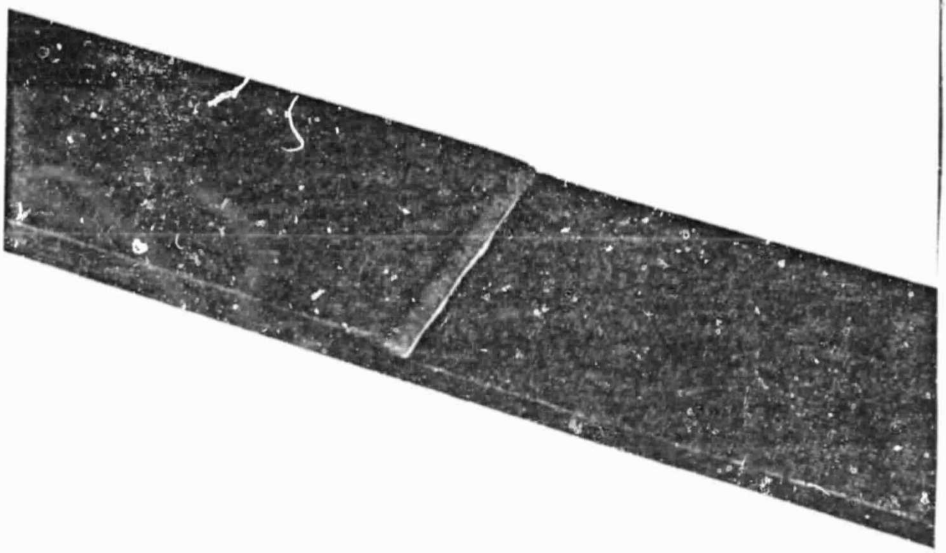

Figure 3. Simulated Stiffener Joint

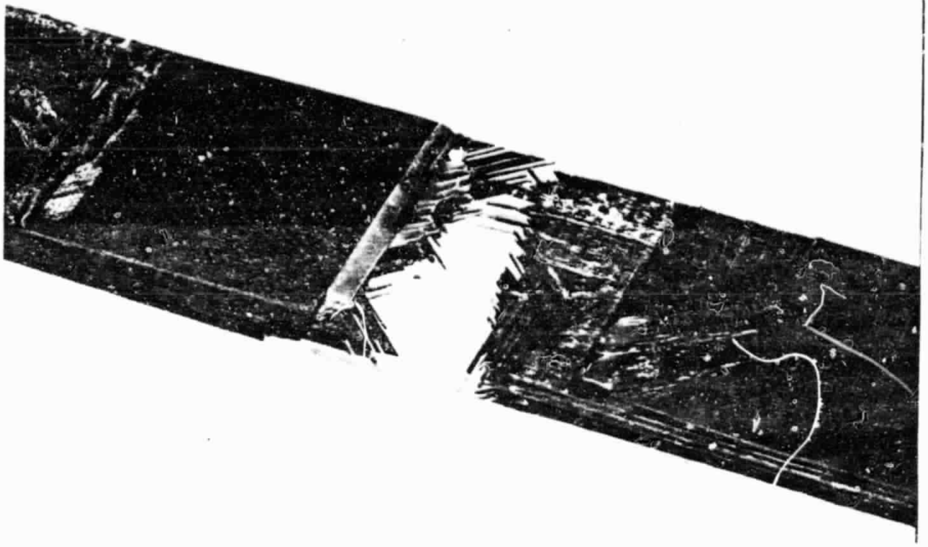

Figure 4. Specimen Failed in Tension

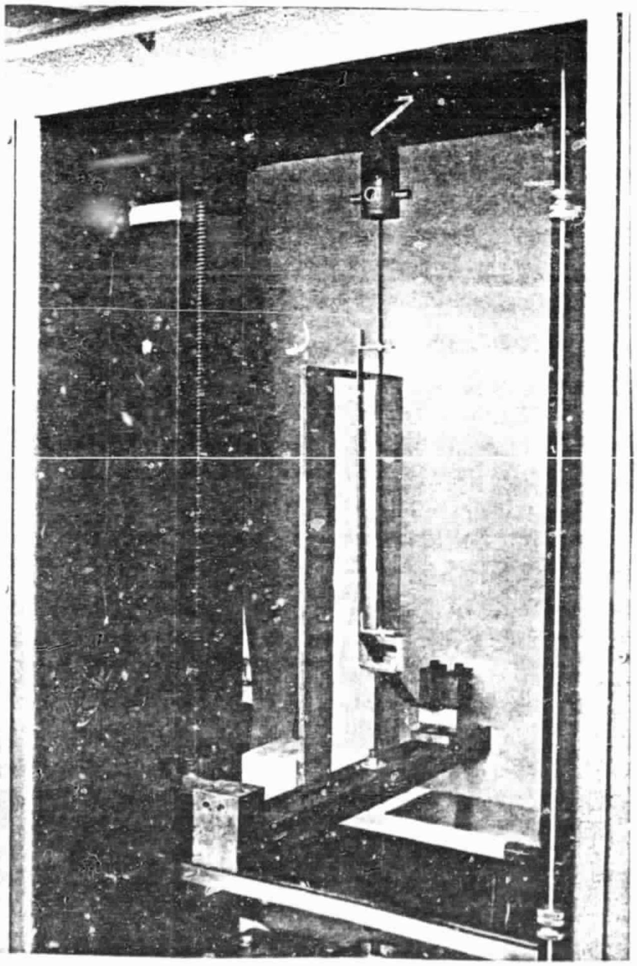

Figure 5. Loading System for Bending-Shear Tests

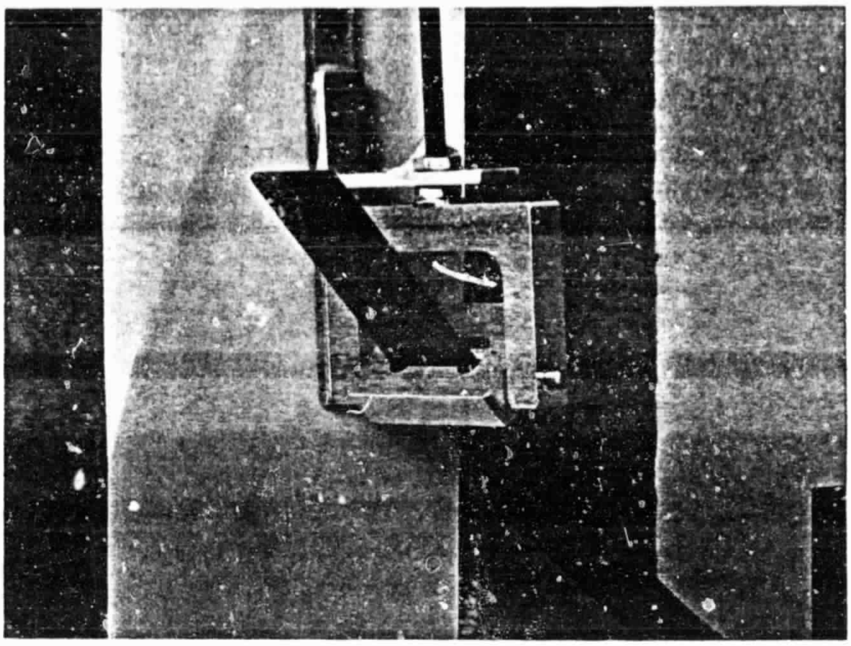

Figure 6. Loading Fixture for Bending-Shear Tests

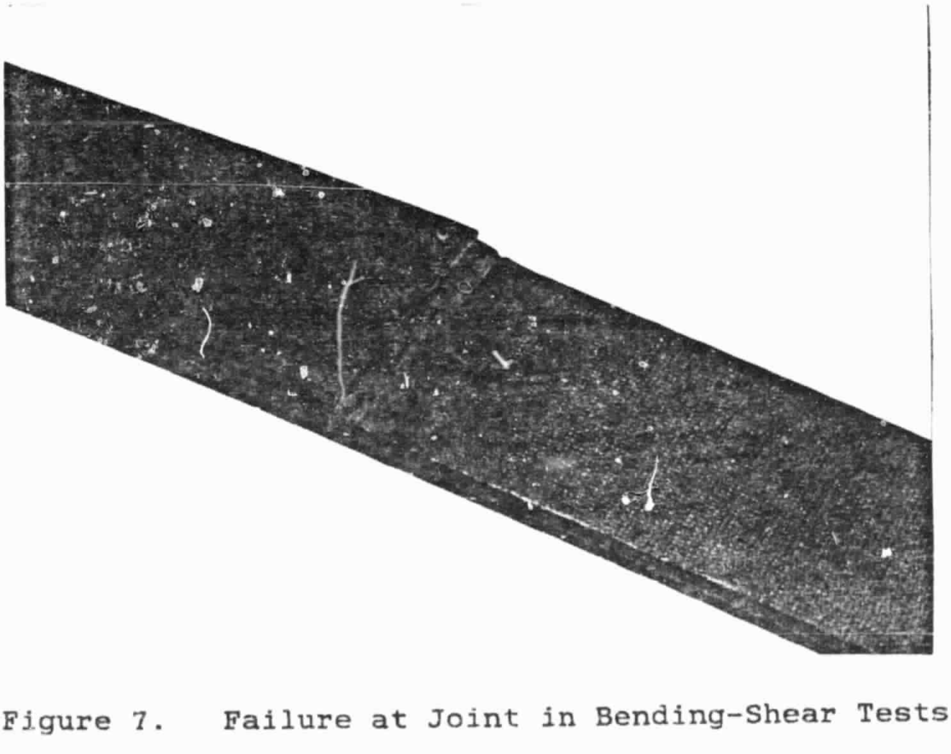

Figure 7. Failure at Joint in Bending-Shear Tests

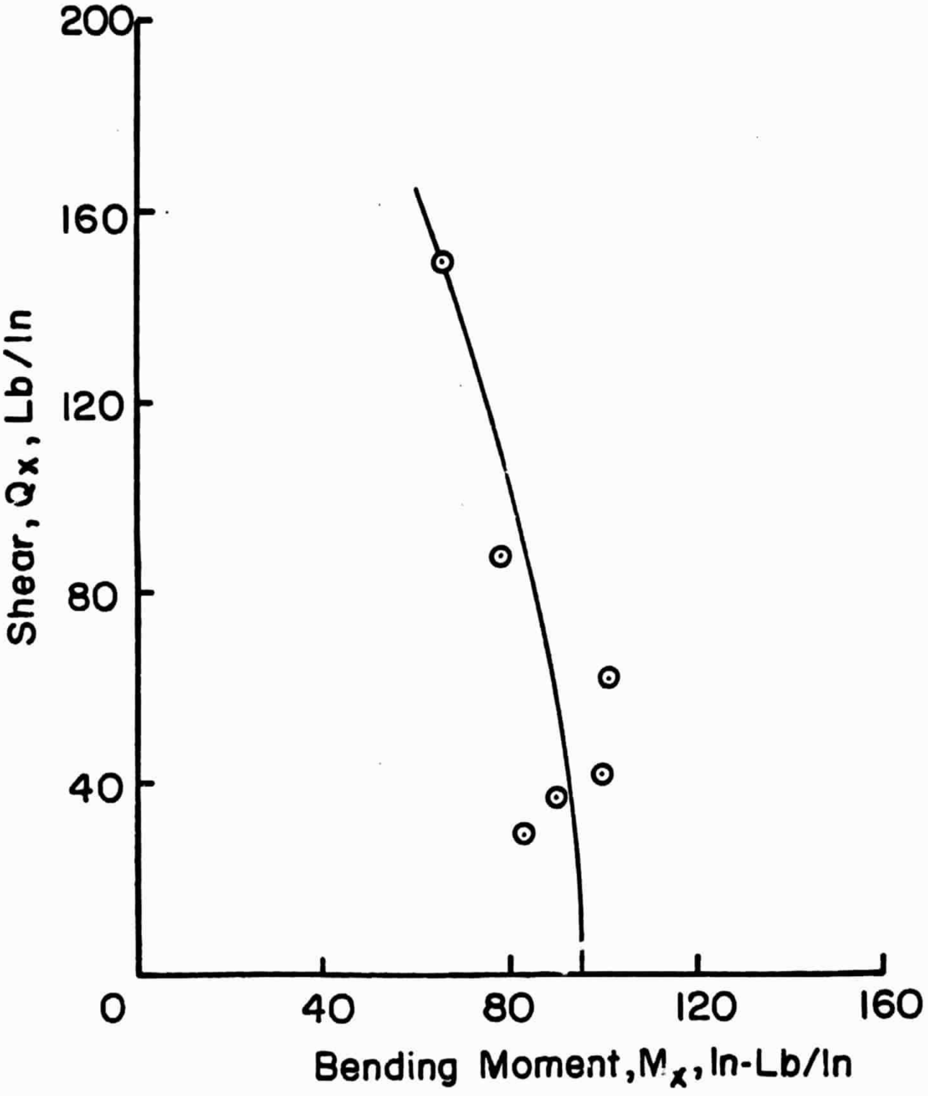

Figure 8. Bending Moment-Shear Failure Envelope

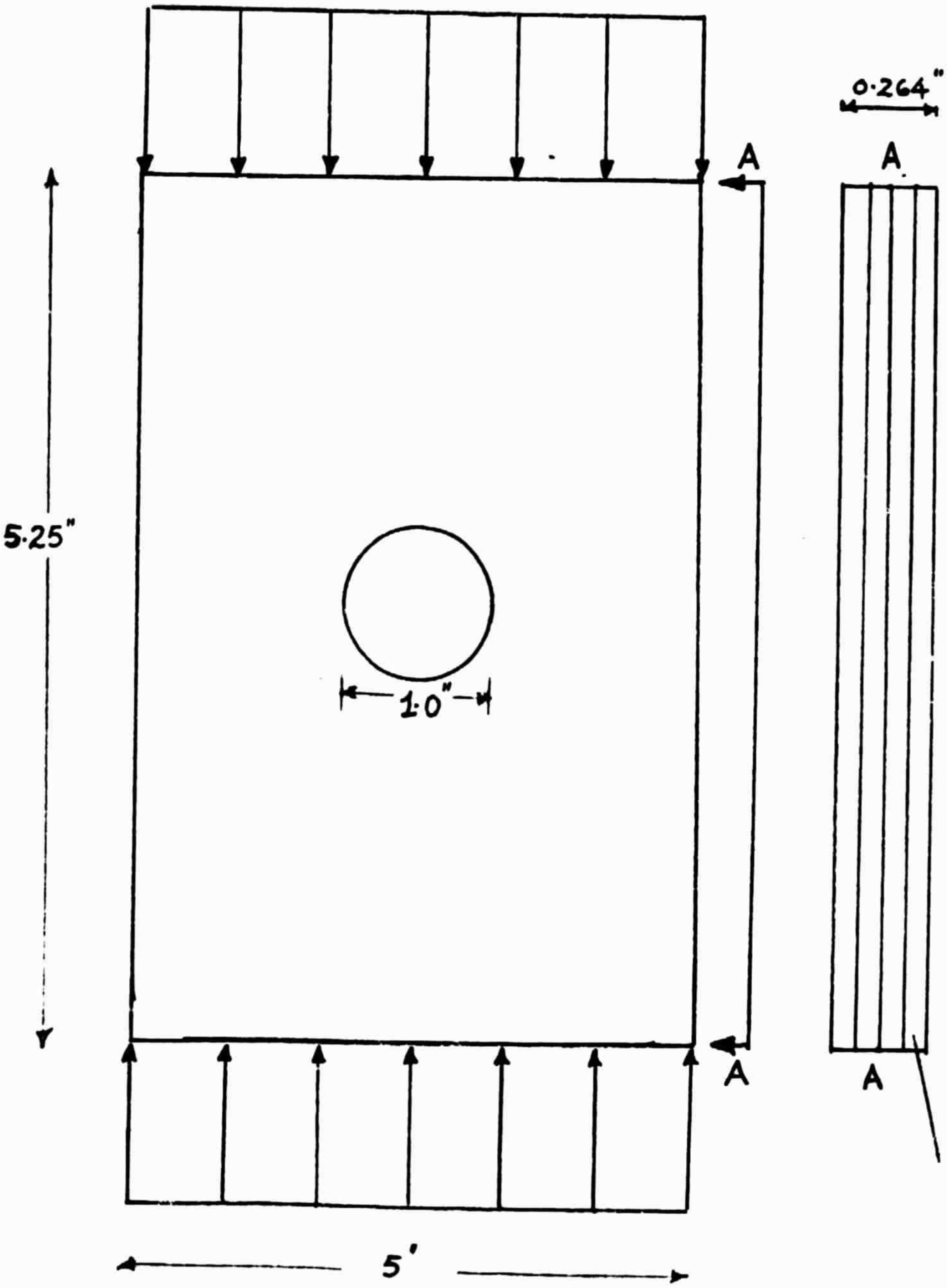

Figure 9. Dimensions of Test Specimen

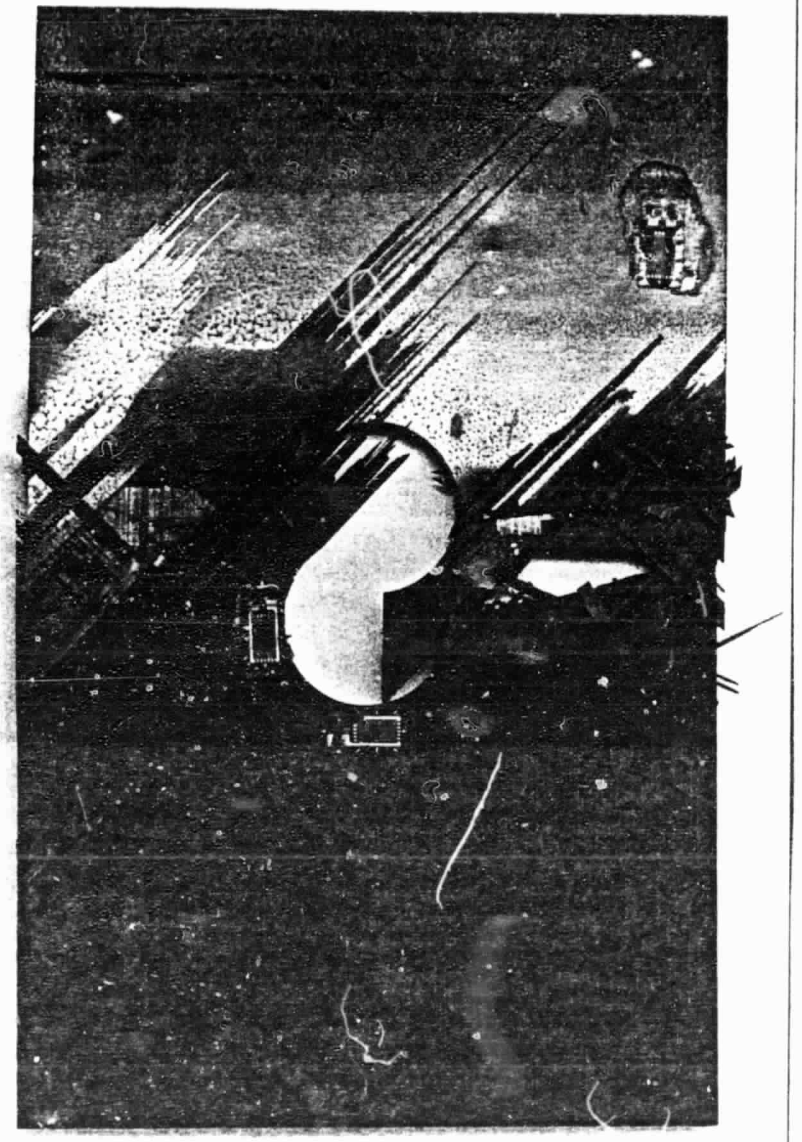

Figure 10. Failure of Plate with Circular Hole

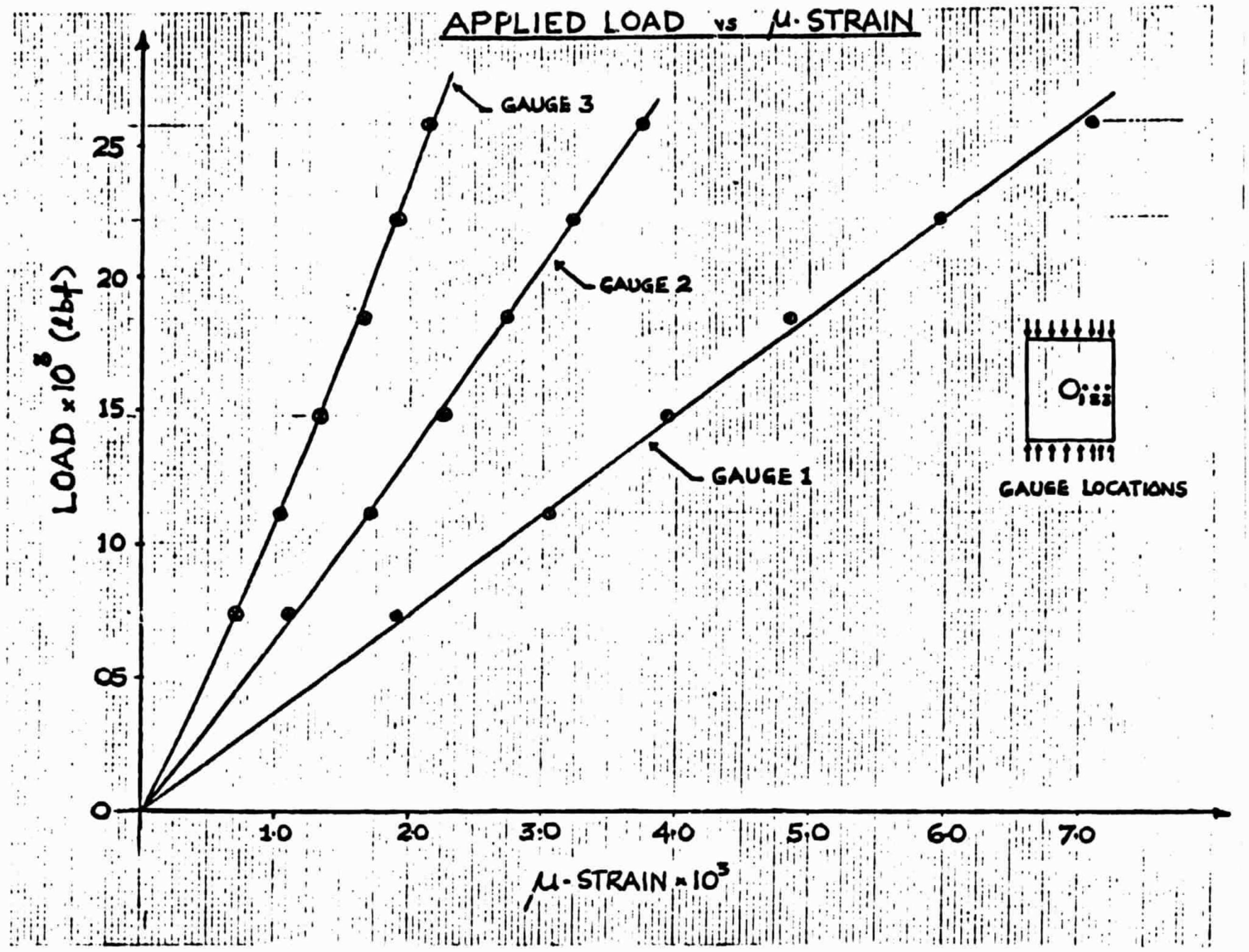

Figure 11. Strain Gage Data from Circular Hole Tests

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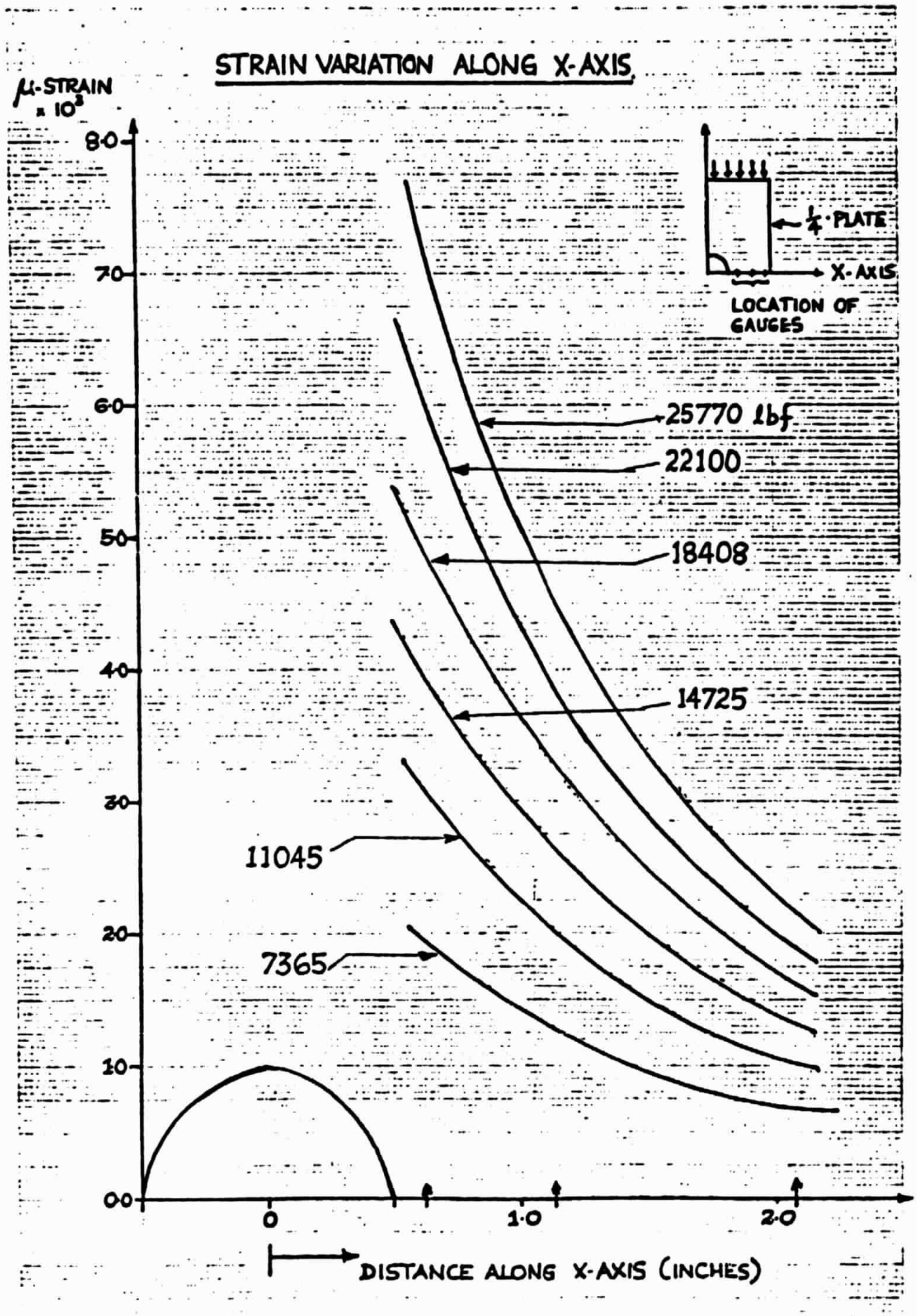

Figure 12. Cross Plot of Strain Gage Data

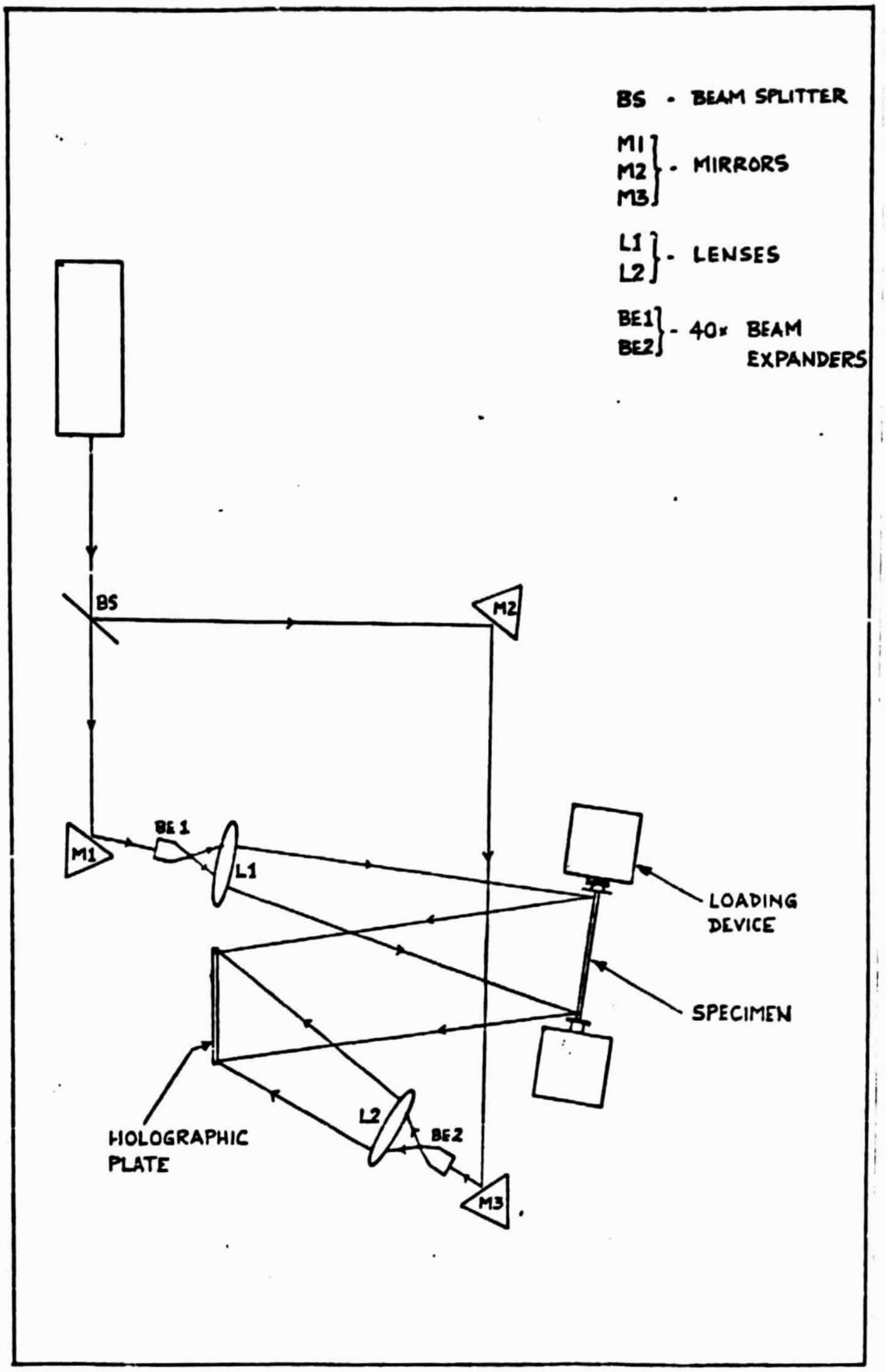

Figure 13. Experimental Setup for Holographic Tests

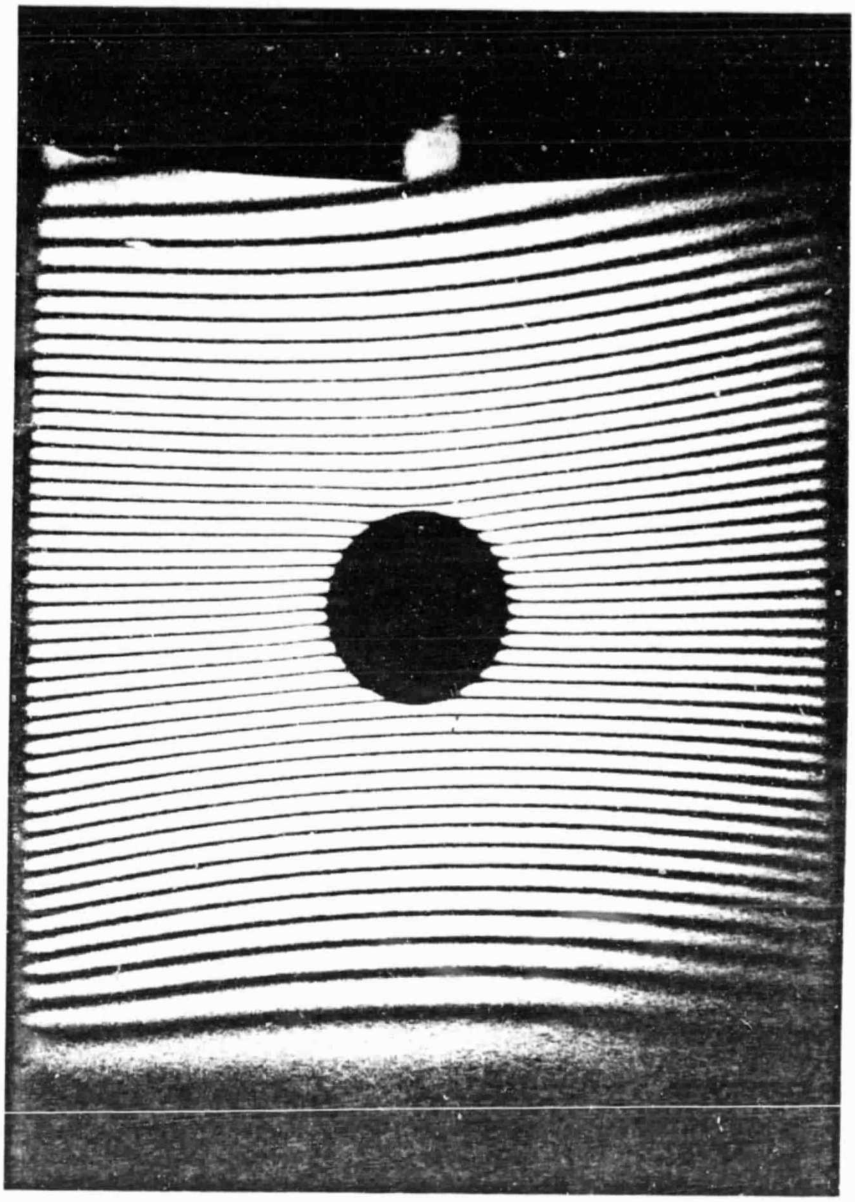

Figure 14. Holographic Interferogram of Plate with Hole Loaded in Compression

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