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Terry V. Roszhart
Jack R. Bohn

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13. ABSTRACT

An experiment is described which uses live fringe holographic interferometry to observe static fatigue in glass. A characteristic holographic fringe pattern has been observed which indicates the existence and location of minute flaws propagating in a glass specimen subjected to a constant load. The fringe pattern is observed continuously as the crack propagates through the material thereby permitting detection of impending failure as much as 20 minutes prior to spontaneous fracture. The results of the experiments demonstrate that live fringe holographic interferometry offers the investigator a new technique for the detection, observation, and control of flaw growth in brittle materials.

Due to the complexity of rigorous fringe analysis and the lack of a usable mathematical model for deflections caused by a crack in a bending beam, the results of these experiments are discussed in a semi-quantitative fashion. It appears that crack growth occurs exponentially in time although the amount of data is not sufficient to statistically determine empirical relationships accurately. The ability of holographic interferometry to obtain both qualitative and quantitative data coupled with the highly coherent pulsed ruby laser system discussed in Part I of this program could permit the application of these techniques to design oriented failure problems as well as theoretical fracture studies.

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HOLOGRAPHIC CHARACTERIZATION OF CERAMICS

Part II

(Observation of Static Fatigue)

Terry V. Roszhart
Jack R. Bohn

15 July 1971

D D C

SEP 20 1971

TRW Systems Group
One Space Park
Redondo Beach, California 90278

FOREWORD

This report describes research conducted on a program sponsored by the Naval Air Systems Command, Department of the Navy under Contract No. N00019-70-C-0136. Overall technical direction was provided by Mr. Charles F. Bersch, Code AIR 52032A, of the Naval Air Systems Command. This report covers work during the period May 15, 1970 to June 15, 1971.

Project engineer for this program was Terry Roszhart. The work was performed by the Materials Technology Staff under the supervision of J. R. Bohn. The authors wish to acknowledge the assistance of their associates, especially Martin D. Cawley.

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studies.

CONTENTS

LIST OF ILLUSTRATIONS

I. INTRODUCTION

This report describes an experimental investigation which uses holographic interferometry to study the propag__ion of surface flaws that lead to failure in brittle materials. By using holographic interferometry to monitor a glass specimen subjected to a constant load, it has become possible to detect microscopic cracks and to observe their growth as they propagate to failure. These cracks are indicated by a characteristic pattern of dark fringes superimposed on the material surface by the holographic process. Both the size and location of the flaw is indicated by the fringe pattern and the time of failure can be estimated quite accurately. Flaw propagation has been detected as early as 20 minutes prior to fracture under a constant load. By using live fringe holographic interferometry, it is possible to observe this fringe pattern in real time allowing the experimentor to accurately predict the location and time of impending failure.

For the purpose of these experiments, a special dead weight loading device was designed, constructed, and incorporated into a helium-neon continuous wave holographic system. The loading device was designed to place a constant bending stress in a glass beam while leaving the tensile surface optically accessible for holographic interferometry. Live fringe interferograms were constructed of glass microscope slide specimens by 1) holographically exposing a photographic plate to the loaded specimen, 2) developing the plate into a hologram, 3) and accurately relocating the plate in the holographic interferometer. The fringe pattern characteristic of a crack was observed through the hologram and photographed with a 35 mm camera. The time under load was automatically recorded when each photograph was taken.

A rigorous mathematical analysis of the results obtained in these experiments was not attempted at this time due to the complexity of evaluating holographic fringe patterns and the lack of an adequate mathematical model describing the deflections of a beam containing a dynamic three-dimensional crack. However, the holographic fringe patterns

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observed are shown to be the result of out-of-plane deformations. These deformations are caused by a loss of load bearing material as the crack expands in the stressed beam and serve to indicate the approximate size of the flaw.

Results of these experiments indicate that the crack extends in time exponentially, as has been reported by other investigators (1). However, the number of tests performed in this investigation was not sufficient to statistically determine empirical relationships accurately. Static fatigue strength measurements taken with the apparatus have also proved consistent with tests conducted by others (2,3,4,5,6,7). However, the experiments conducted in this program differ from conventional crack propagation studies (8,9,10) in that the flaws being observed holographically are microscopic cracks occurring naturally in materials surfaces. The flaws studied in conventional crack propagation experiments are unnaturally large and geometrically restricted. Thus, the results obtained by holographically observing failure in brittle materials may significantly improve conventional strength and propagation studies. In addition, the ability of holographic interferometry to monitor the effects of crack growth in real time provides the experimentor with an unprecedented tool for observing and controlling flaw extension.

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II. SUMMARY

The experiments performed in this investigation have demonstrated
that live fringe holographic interferometry can be used to detect and
monitor the growth of cracks in brittle materials. Cracks have been
detected in glass microscope slides subjected to a constant load by
the formation of a characteristic holographic fringe pattern which indi-
cates the location and approximate size of the flaw. It is possible to
observe these flaws as much as 20 minutes prior to the failure of the
specimen and the propagation through the brittle material can be moni-
tored continuously. The static fatigue strength measurements obtained
in this study compare well with similar measurements taken by other
investigators. In addition an exponential growth rate of the holographic
fringe pattern may be related to the characteristic exponential time
propagation of material flaws.

Restrictions of the techniques described in this report are
imposed only by limitations of the particular equipment used in this
study and are not indicative of the general potentials of holographic
instrumentation and fracture mechanics. For example, the development
of a highly coherent pulsed ruby laser reported in Part I of this
basic program (11), makes the holographic observation of dynamic frac-
ture events feasible. The object size limitations of CW holography
is also overcome with the pulsed ruby laser which has been used to
holographically image scenes as large as 1000 cu. ft. The use of holo-
graphic plate holders which provide development of photographic plates
in less than 1 minute would also significantly increase the usefulness
and success of the techniques described above. Finally, these tech-
niques need not be restricted to the 4-point beam bending configuration
used in this study, thereby permitting the holographic observation of
testing configurations for which rigorous mathematical models exist.

The most apparent feature of this study is the qualitative
detection and monitoring of propagating cracks in brittle materials
which has been performed in the above experiments. Although these

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tests were performed in the laboratory, it may be feasible to extend them to field-oriented problems where they could augment existing holographic nondestructive testing techniques. The ability to locate a failure-producing flaw may also prove useful in biaxial tests where the uniform distribution of stress is often difficult to obtain. It has been seen from this study that an irregular stress state can be characterized by holographic techniques so that the conditions at the exact point of failure can be accurately computed. Such applications could include the study of failure in windshields, observation ports, and radomes which have been subjected to typical service loads and environments.

The results obtained in this study also indicate that the holographic instrumentation may prove useful to the study of fracture mechanics in a more fundamental manner. The potential of holographic interferometry to accurately determine deformations at all points of a material's surface may provide the ability to characterize flaws in multi-dimensional parameters. Thus, it may be possible to nondestructively measure the three-dimensional boundary of a flaw as the flaw propagates through a stressed material. This ability could be most helpful in characterizing the changes in stress intensity factors along the boundary of a natural flaw and could monitor the interaction of a crack boundary with material irregularities such as phase changes, voids, or fibers. While these problems require a degree of experimental and analytical sophistication that has not yet been attained, holographic techniques may prove instrumental in these areas of fracture mechanics.

III. BACKGROUND

The basic objective of this overall investigation has been to
study the application of several different holographic techniques to
a variety of problems encountered in ceramic processing. An earlier
study (11) has demonstrated the application of holographic interfero-
metry, microscopy and correlation to such problems as residual stress
measurement, property evaluation, nondestructive testing, particle
analysis, and dimensional control. It was also noted in the previous
study that holographic interferometry could be effectively applied to
an investigation of brittle fracture and crack propagation. Since
this seemed an obviously important aspect of ceramic materials behavior,
it was chosen as the subject of this program.

The early attempts of modern investigators to characterize
material strength in terms of cohesive properties quickly focused atten-
tion on the weakening effects of microscopic voids, cracks, and other
material flaws. The difference between the theoretical strength and
the measured ultimate strength was attributed to the increased stress
intensity resulting at a material irregularity. The various stages of
the fracture process, in fact, may be viewed as the extension or growth of
small flaws to the size of the structural cross section resulting in frac-
ture or separation of the material. The velocity of this extension is
comparatively slow until the flaw reaches a specific dimension known as
the critical length. At this point the crack velocity increases in
an unstable manner as the flaw propagates to failure.

Various features characteristic of failure in brittle materials
have been observed experimentally and can be explained empirically by
this concept of fracture. For example, the relatively large scatter
of data found typically in ultimate strength tests of brittle materials
is attributed to the statistical distribution of flaws occurring in
the material (12). In addition, the tendency of ceramic materials to
fail at stresses less than the nominal ultimate stress is the result
of the growth of microscopic flaws. This phenomena is usually referred

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to as static fatigue (2,3,4) and is studied by determining the time needed for failure to occur in a brittle material subjected to a constant load. Static fatigue tests under controlled environments have shown the influence of atmospheric properties on the strength of brittle materials. These tests testify to the mechanical and chemical nature of the flaw propagation phenomena.

Holographic interferometry (17) has three distinct features which make it well suited for studying deformations of a material undergoing fracture. These features are 1) sensitivity to deformations less than 10 microinches, 2) measurement of deformations occurring at all visible points of the material surface and 3) observation of these deformations at the same time they are occurring. These deformations are indicated by dark bands that appear projected on the illuminated object under study. The bands are called fringes and are formed by the holographic interferometric process when the object undergoes either rigid body translations or deformations. In general, both the magnitude and direction of the material deformations can be computed from the number and general pattern of these holographic fringes. The fringes are influenced by deformations as small as 10 microinches and can detect deformations at all points of the object that can be seen by the observer through the hologram.

Holographic interferometry can be performed in two slightly different forms, depending upon the particular features of the deformation process being studied. The form used in this study is called live fringe interferometry and permits observation of material deformations as they occur in real time. The technique consists of forming a hologram of an unloaded object and then superimposing the loaded object with its holographically formed image. By viewing the object and the carefully positioned image through the hologram, a fringe pattern can be seen which indicates deformations occurring relative to the state of the object at the time the hologram was first formed. This fringe pattern changes as the strain in the object changes, and these changes

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can be viewed through the hologram or photographed with a camera. Thus it can be seen that holographic interferometry can conveniently observe minute deformations resulting from the growth of a flaw in brittle materials.

A description of the techniques involved in live fringe holographic interferometry is given below. A more general review of holography and holographic instrumentation for materials studies is provided in the literature (13-25).

IV. LIVE FRINGE HOLOGRAPHIC INTERFEROMETRY

Live fringe holographic interferometry is basically a two-step process requiring the use of coherent monochromatic light emitted by an optical laser. The first step consists of forming a hologram of the object to be viewed. During the hologram construction, light from this laser is divided into two beams. The first beam is used to illuminate the object and the second beam is used as a reference wave. This is shown schematically in Figure 1. The scene beam A reflected from the
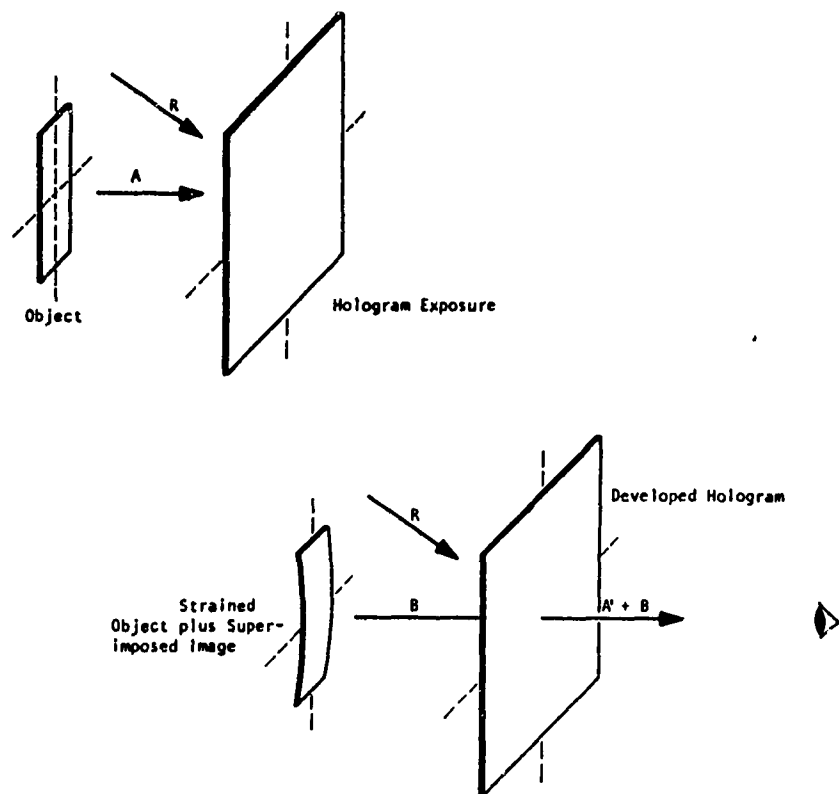

Figure 1. Live Fringe Holographic Interferometry.

object is directed at a photographic plate where it is mixed or added to the reference wave R which arrived at the film through an arbitrary, but different, angle. Due to the coherence and monochromatic nature of laser light, these two beams superimposed vectorially into a wave field which is stationary in space, and therefore, recordable by the photographic plate.

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During this exposure the components of the scene wave have been coded by the reference wave in a manner that permits decoding after the film has been developed. This decoding process is accomplished by illuminating the developed photographic plate with the original reference beam R. Most of this beam passes directly through the hologram and is of little value. A sufficient amount, however, is diffracted by the hologram to produce a copy of the initial object wave, A'. This wave continues in the direction of the original wave so that the holographic image can be viewed by looking through the hologram just as one looks through a window. The image appears at the location of the original object.

The second step of the live fringe interferometric process consists of relocating this hologram in the original apparatus that was used to construct it. This relocation must be accomplished to within the limits of half a wavelength of light. This can be easily accomplished through the use of kinematically mounted photographic plate holders. The hologram is then illuminated with the original reference beam R, and the object is again illuminated by the coherent laser light. As the object deforms slightly, it propagates a new object wave front B, which passes through the developed hologram. At this point, the new object wave front B is added to the reconstructed object wave A'. This wave front addition is both complex and vectorial in nature and is fundamental to the holographic interferometric process.

Light waves are complex quantities that add vectorially when propagating through the same regions of space. When two waves of equal amplitude have phase components differing by π or 180° their $\bar{E}$-fields are pointing in opposite directions and their vector sum thereby vanishes. Conversely, when two waves have equal amplitude and phase components their sum is doubled. Under proper conditions of illumination and observation, two wave fronts can be superimposed such that the images of the original object are also superimposed. If the physical differences of the objects are slight, two images combined to form a single image with dark regions of opposite phases. These dark regions group together into dark bands that are projected across the object and are referred to as holographic fringes.

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The analysis needed to interpret fringe patterns in terms of
material deformations was first presented by Haines and Hildebrand (19)
and centers on the notion that all possible view points receive light
scattered from all points of the reconstructed objects. The analysis
is quite rigorous and can theoretically be applied to any object under
any form of deformation. However, due to the complexity of the result-
ing equations and the difficulty of experimentally measuring some of the
needed parameters, complex objects under complicated loads are often
difficult to analyze. By carefully choosing the variables of illumina-
tion and observation, this difficulty can be reduced (20). If the object
is illuminated by a collimated parallel beam and observed through a
small aperture the problem can generally be solved by ray tracing tech-
niques. In addition, if specimen loads are such that one or two degrees
of motion are negligible, both the fringe analysis and elastic stress-
strain analysis are simplified.

In many cases, the early incorporation of the above approximations
into a testing system greatly simplifies analysis of holographic inter-
ferograms. For example, the conditions shown in Figure 2 describe holo-
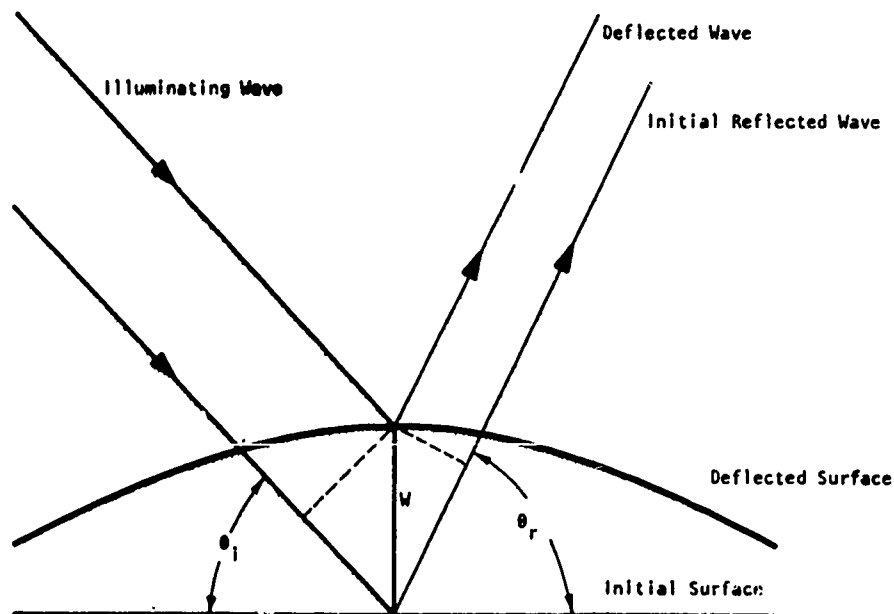graphic analysis of flat plate deflection. In addition to the above

Figure 2. Ray Trace for Holographic Analysis of Plane Deflections.

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illumination and observation approximations, it is assumed that plate deflections W are normal to the initial plane of the plate. This is plausible for small deformations and is consistent with most elastic theories of plates and beams. By summing the total change in path length as a function of beam displacement and dividing by odd values of one half wavelength, the following equation is derived:

$$W_n = \left(\frac{2n-1}{2}\right) \frac{\lambda}{(\sin \theta_i + \sin \theta_r)}$$

W_n = beam deflection at point n

λ = wavelength of light

θ_i = angle of incidence

θ_r = angle of observation

The integer n is the number of fringes between the point where W_n is occurring and a point on the beam that undergoes no deformation. This equation can be used to determine either the deflection or radii of curvature at any point and is readily applied to most elastic theories of flat plates and beams.

V.   EXPERIMENTAL APPARATUS

The apparatus needed to accomplish the goals of this investigation had to meet two sets of requirements. To provide accurate strength measurements, the loading device must create stress states in the material that are easily reproduced from one test specimen to another. The stress should be uniform in a sufficient portion of the specimen to permit quantitative analysis of the stress conditions causing failure. Studies by other investigators have demonstrated the detrimental effects of irregular or parasitic loads. In addition, the environment of the material has an influence on the strength of brittle ceramics such as glass. Thus, the device must be enclosed in an environmental chamber to permit accurate control of the environmental temperature, pressure, humidity, and composition.

Since the specimen under load is to be observed holographically, the loading device must also meet a different set of optical requirements. When the source of light for a holographic process is a CW laser, all components of the optical system must be dynamically stable. This means that the load applied to the specimen must be constant particularly if the test is to be conducted over a long period of time. All structures in the system must be rigid enough to prevent extraneous motion but must also oe designed to dampen building or room vibrations. These requirements were met by the equipment shown in Figures 3, 4 and 5.

The loading system is shown schematically in Figure 3. A four-point beam bending configuration was chosen since its usefulness for the testing of brittle materials has long been established. The apparatus is completely enclosed in an environmental chamber. The device can apply a maximum load of 100 pounds and can accommodate specimens as large as 7 inches long, 1 inch thick and 1-3/4 inches wide. The loading linkage is oriented to permit visible access to the tension side of the beam. The base of the device is designed to eliminate rigid body motion of the sample caused by application of the load or changes in the environmental chamber pressure.
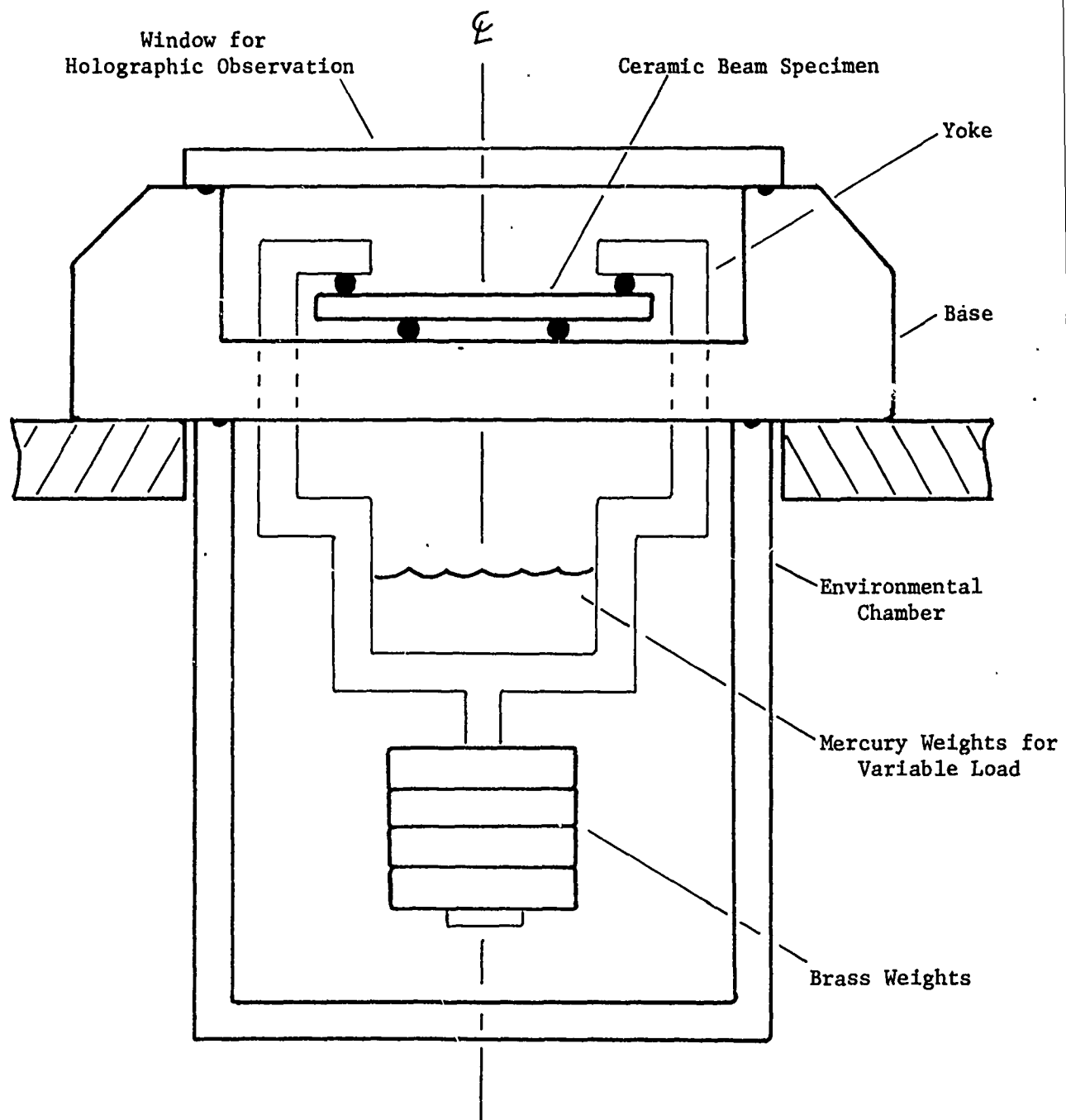
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Figure 3. Schematic of Deadweight Loader.

A constant load is applied to the beam specimen by 1/4-inch
roller bearings attached to a yoke which in turn is fastened to a system
of dead weights. This weight system consists of a hollow container of
mercury and a set of calibrated brass weights, both of which hang below
the table base. The brass weights are used to determine the approximate
load of the device, and the mercury is used to permit finer adjustment
of this load. The volume of mercury in the container can be measured with
an accuracy of 1/2 ml permitting adjustment of the load to within .015
pounds. Photographs of the dead weight loader and holographic system
are shown in Figure 4.

The optical system is described schematically in Figure 5. A 15
milliwatt CW HeNe laser was used to illuminate the object and hologram,
the beam of light from the laser was passed through a spatial filter
collimated into a 2-inch diameter beam and divided by a beam splitter.
One portion of the beam is guided by mirrors M1 and M2 onto the specimen
from which it propagates to the photographic plate H. The second beam
is used as the reference beam for the hologram and is directed upwards
at the photographic plate by mirror M3. The intensities of the two
beams are controlled by neutral density gelatin filters and the holo-
graphic exposures are controlled by a mechanical shutter. Once the
photographic plate is holographically exposed, it is developed
into a hologram and returned to its original position above the dead
weight loader. This relocation of the photographic plate is accomplished
with an accuracy of $\frac{\lambda}{2}$ ($\sim$ 10 microinches) by means of a specially designed
kinematic plate holder. The interferogram indicates deformations occur-
ring on the specimen as viewed from above the hologram. A 35 mm camera
can also be mounted above the hologram to photograph the interferometric
fringe pattern.

Although the dead weight loader can test a variety of specimen
sizes, glass microscope slides were used in this study due to their
accessibility. Since other investigators (1,2,8) have also used micro-
scope slides for their studies, these specimens were judged adequate for
the purpose of this project. The slide was made of a common soda-lime
glass and measured 1-1/2 inches wide by 3 inches long. Thickness varied

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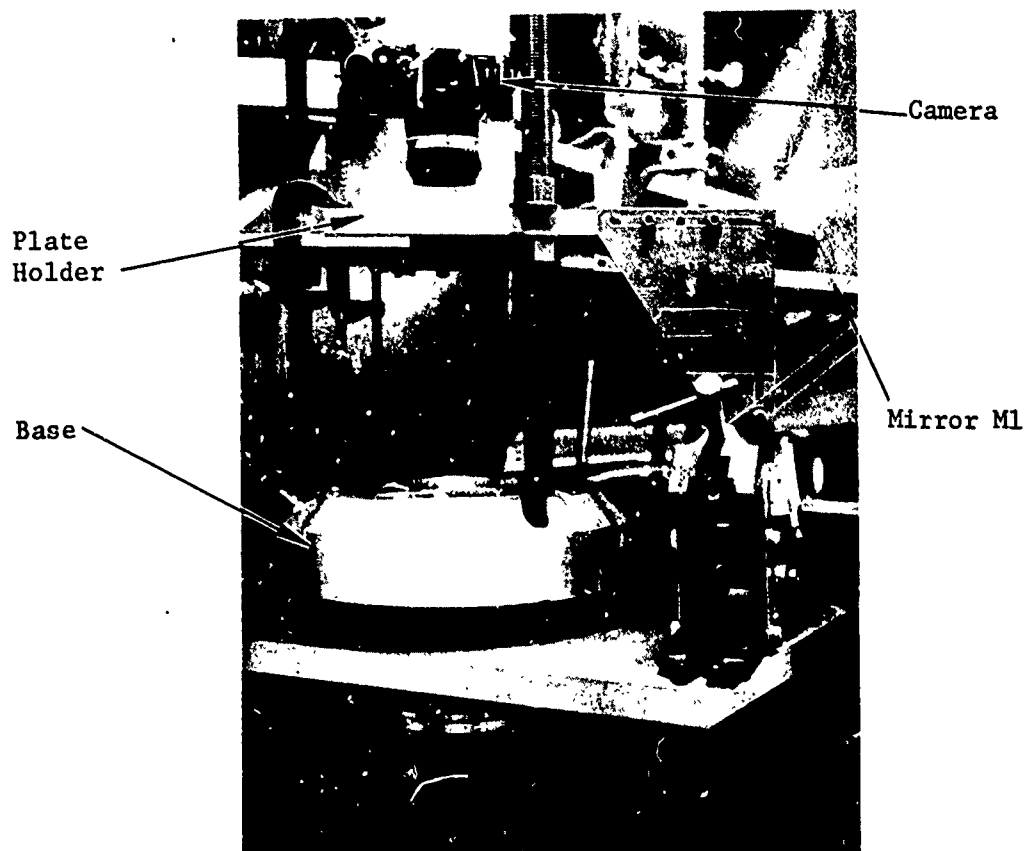
a) Side View
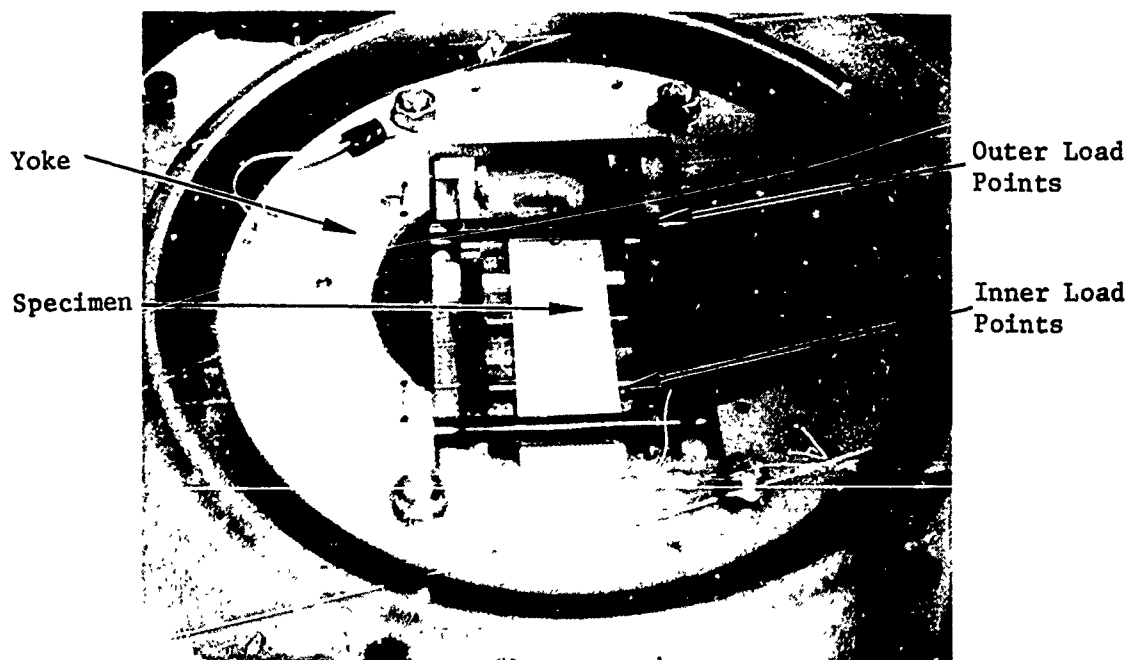
b) Loading Chamber

Figure 4. Photos of Deadweight Loading Device.

from .045" to .052". The edges were ground but not beveled. All speci-
mens were screened for chips, scratches, and nonconstant thickness. Since
the exact history of the slides was not known, strict control of the
storage environment was not maintained.

Recent studies by Nordberg, Mochel, Garfinkel and Olcott (26)
and others (27) have shown that the tensile strength of glass can be
significantly increased by the characteristic introduction of residual
compressive stresses localized near the surfaces of the material. These
stresses are produced by the substitution of K^+ ions for the smaller Na^+
ions in the glass structure. This substitution can be accomplished by
immersing the glass specimen in a bath of molten KNO_3 at a temperature
of 705°F for a period of 24 hours. Some of the specimens used in this
study were chemically strengthened in this manner and the resulting
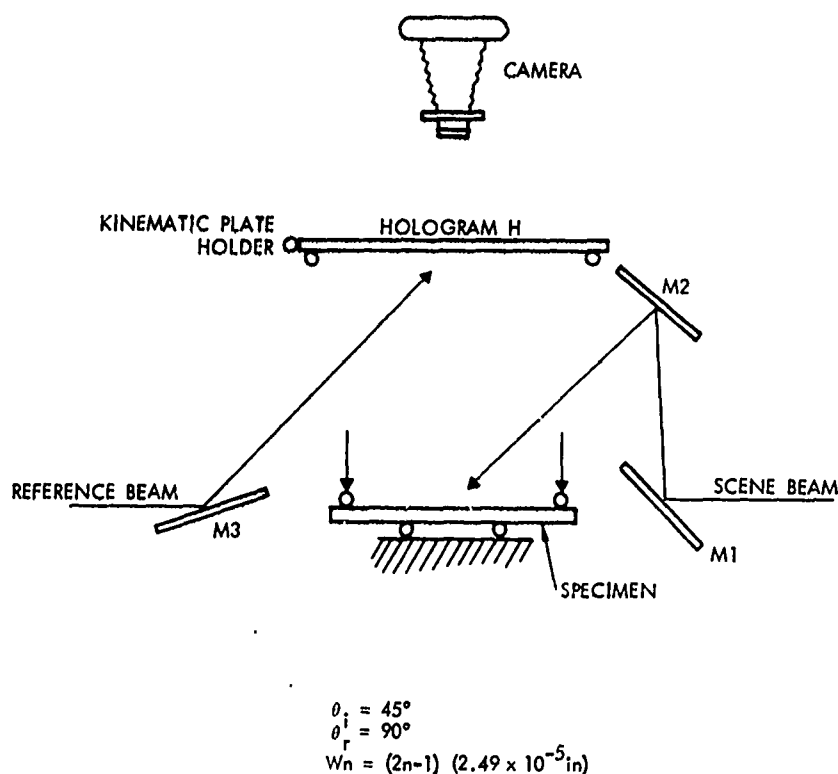increase in strength was measured.

$\theta_i = 45°$
$\theta_r = 90°$
$W_n = (2n-1) \ (2.49 \times 10^{-5} \text{in})$

Figure 5. Schematic Representation of Holographic Apparatus.

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VI. TESTING TECHNIQUES AND PROCEDURES

The first application of the equipment described above was to determine the uniformity of the stress states created by the dead weight loader. Since holographic interferometry can determine deformations over the entire visible surface of a specimen, it is inherently well-suited to monitoring uniformity of stress or strain. A glass slide was painted on one side to provide an opaque surface and placed in the dead weight tester. An initial load of 2.5 ksi was applied and a hologram was made of the specimen. The hologram was made by placing a photographic plate in the kinematic mount and exposing the plate to both laser beams for 1/4 of a second. The plate was left in place while an increase in load of 1.3 ksi was applied. A second exposure of the photographic plate was made of the specimen in the second state of stress.

The photographic plate was removed and photographically developed into what is commonly called a dead fringe hologram. Interference fringe patterns seen in the hologram are shown in Figure 6, and are indicative of the change or deflection occurring between the two states of stress of the microscope slide. It can be seen that the stress in the beam is moderately uniform in the region between the inner load bearings. However, a slight irregularity is evident in this region and is a result of the
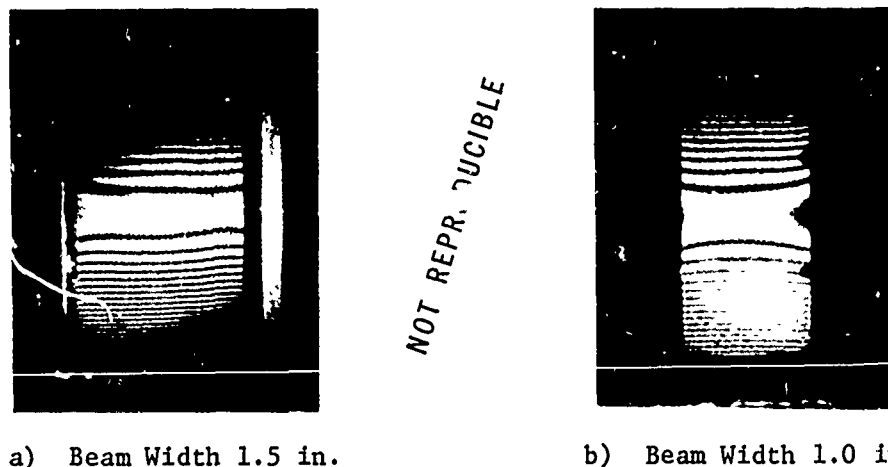

a) Beam Width 1.5 in.   b) Beam Width 1.0 in.

Figure 6. Loading Pattern of Deadweight Loader Observed with Holographic Interferometry. Deflection of Beam was Increased Between Exposures.

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plate-like behavior of the glass microscope slide. This anticlastic
curvature was also evident in microscope slides with a width of only
1 inch and suggests that a bending plate analysis might be more accurate
than a bending beam analysis.

Static fatigue tests were run on these glass slides by measuring
the time needed for a constant load to cause failure. An electric
switch was added to the loading device to start a clock as the load was
applied to the specimen. The clock was automatically stopped by the same
switch when the specimen broke, thus recording total time T that the load
was applied to the material. Both the amount of load applied to the
specimen and the time to failure were recorded. Since the static fatigue
strength of brittle materials is influenced by the roughness of the
tensile surface, a slight amount of abrasion was introduced to reduce the
scatter of the results. This was accomplished by masking off all but a
center 3/4-inch square of the glass slide. This center square was lightly
abraded with 320 grit emery paper applied with finger pressure. This
served to adequately control the abrasion on all the samples and eliminated
formation of starter cracks at the specimen edges.

The results of these tests are summarized in Table I (Figure 7)
and Figure 8 and are discussed in a later section.

Once the approximate relationship between stress and time to
failure had been established, the failure of glass beams was studied
using holographic interferometry. Microscope slides were measured and
abraded as described above. In addition to this treatment, the tensile
side of the beams located between the outer load points was painted with
a flat diffusing paint. This provided an opaque surface on which the
holographic fringes could be formed and observed. Static fatigue tests
of these specimens could find no significant effects of the paint on
the ultimate strength of the glass, or of the time T needed for failure
under a constant load. After the specimens had been prepared in this
fashion, they were put in a dead weight device and placed under a con-
stant load. An interferogram of the loaded specimen was then made by
exposing the photographic plate to both the object and the reference beam

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TABLE I

Load (lbs)	No. Specimen	σ_{ave} (ksi)	T_{ave} (sec)	s (standard deviation) (sec)
6.49	2	3.92	32	---
5.93	3	3.38	211	---
4.80	2	2.65	405	---
4.50	12	2.56	758	565
4.23	14	2.29	4,180	3.16×10^3
15.6	17*	10.21	851	2.1×10^4

*Chemically strengthened

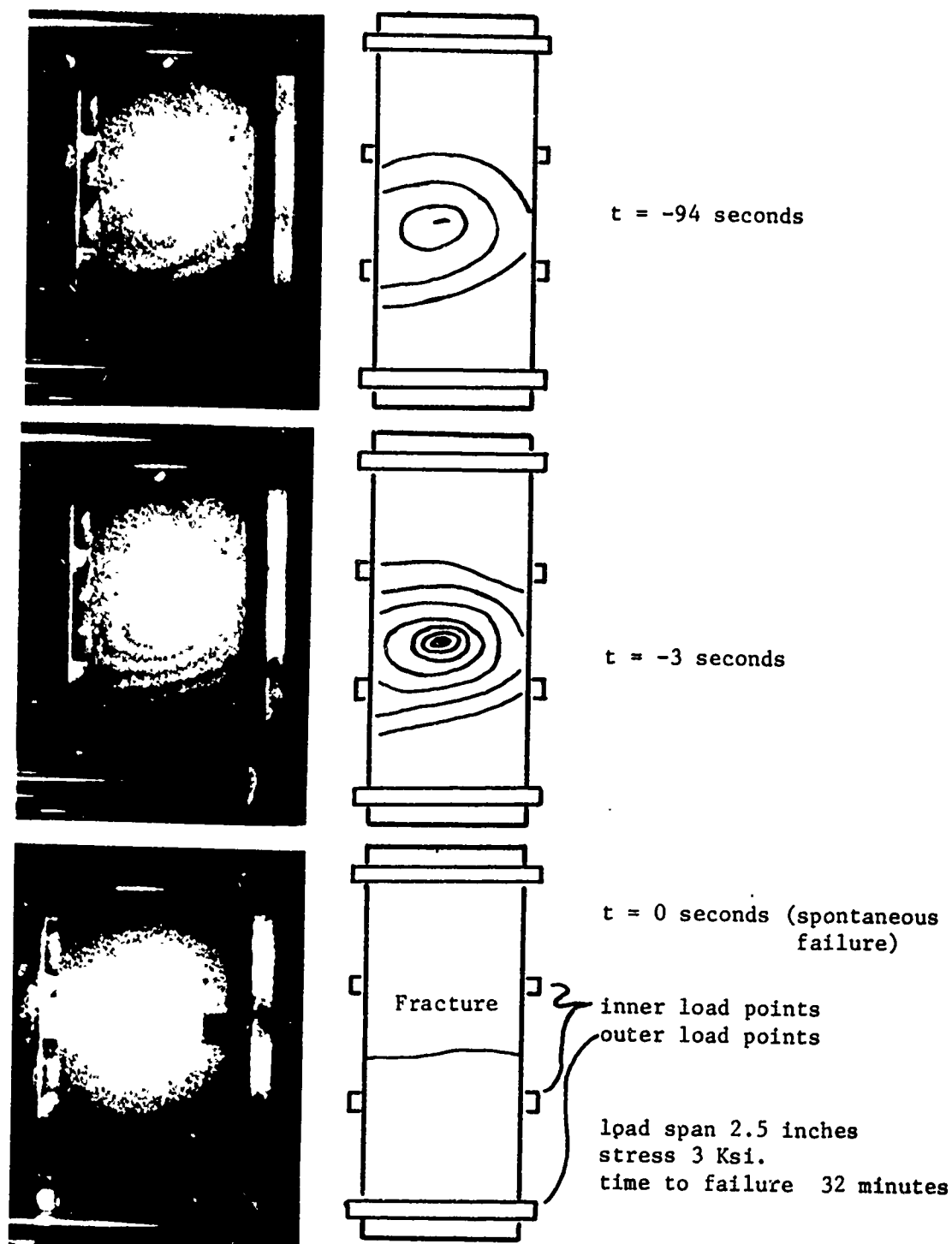Figure 7. Summary of Static Fatigue Data.
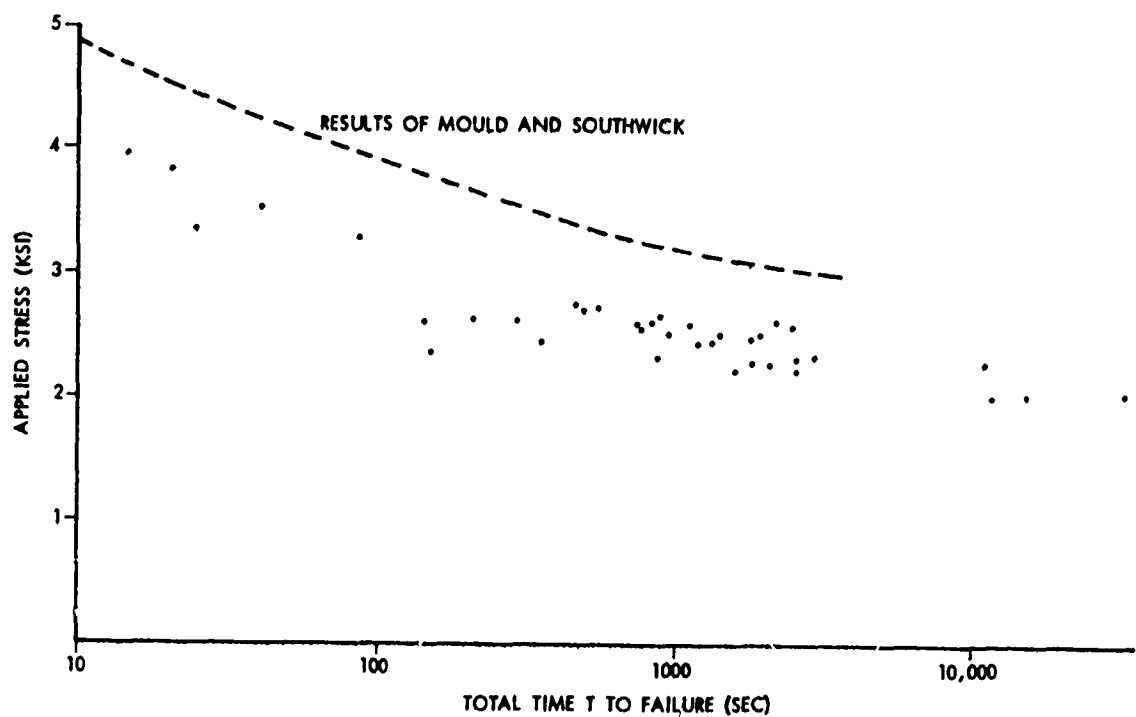
Figure 8. Static Fatigue Curve for Unstrengthened Soda-Lime Glass.
          (320 Grit Abrasion)

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for 1/2 second. The photographic plate was then developed in K19
developer for 2 minutes, washed for 15 seconds, fixed for 3 minutes
and washed again in running water for 15 minutes. The plate was then
run through an alcohol bath and allowed to dry for a minimum of 5 min-
utes before being relocated in the holographic plate holder.

Once this hologram was accurately replaced a live fringe inter-
ferogram could be observed by looking through the hologram at the loaded
glass specimen. Any deformations of the glass beam was indicated by
fringes which appeared to be projected on the material surface. Move-
ment of the loading yoke was also indicated by fringes. In many instances
the glass beam broke before the hologram could be photographically pro-
cessed, and the test had to be repeated. At other times the loaded speci-
men failed to break within the normal 8-hour day again preventing direct
observation of the fracture. However, on sixteen occasions, the beam did
break within the proper time interval permitting direct observation of
the material crack as it progressed to fracture. In all cases, the same
distinctive pattern of fringes formed around the crack. This pattern
consisted of concentric elliptical fringes that were centered around a
crack and increased in number as the crack propagated. Fringes appeared
to originate at the crack and moved outward across the material surface.
In 6 tests it was possible to photograph the fringe patterns with the
35 mm camera set at f/4 using a 1/2 second exposure. A typical fringe
pattern and its growth as a function of time have been provided to help
identification of the interferometric pattern. The time to failure t
was recorded at the instant the photographs were taken and is indicated
next to each picture. Variations of this fringe pattern that occurred
on two other specimens under similar conditions are shown in Figure 10.

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LIVE FRINGE INTERFEROGRAMS OF CRACK GROWTH IN GLASS

(Static four point bending)

t = -94 seconds

t = -3 seconds

t = 0 seconds (spontaneous failure)

Fracture

inner load points
outer load points

load span 2.5 inches
stress 3 Ksi.
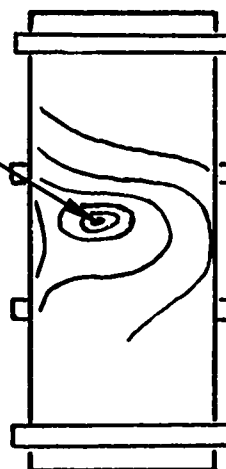time to failure 32 minutes

NOT REPRODUCIBLE

Figure 9. Deformations due to growth of microcracks are indicated by concentric fringe pattern. Note that crack growth can be monitored prior to fracture by increasing number of fringes although crack is submicroscopic.

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σ = 2.71 ksi.

23 sec. before failure

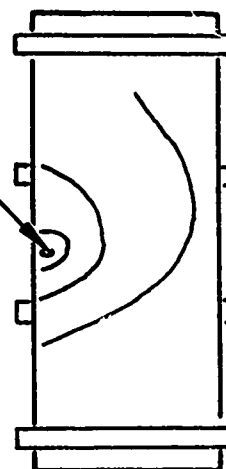NOT REPRODUCIBLE

σ = 2.12 ksi.

5 sec. before failure

Figure 10.   Fringe patterns of cracks growing in two dif-
ferent locations on two similar specimens.

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VII. ANALYSIS AND DISCUSSION OF RESULTS

The results of the static fatigue strength tests performed on
the unstrengthened glass microscope slide specimens are summarized in
Table I and plotted in Figure 8. The vertical axis of this graph
corresponds to the constant strain applied to the glass specimen by the
dead weight loader as calculated from conventional bending beam formula.

$$\sigma = \frac{3}{4} \frac{P\,\ell}{bh^2}$$

σ = stress

P = load

ℓ = length of span

b = specimen width

h = specimen thickness

As mentioned earlier, this ignores the effect of anticlastic curvature
but is the same analysis used by other investigators and is adequate for
the purposes of this report. The horizontal axis of the graph is used
to plot the log of T which is the total time required for the specimen to
fail. The results of Mould and Southwick (2) who prepared, tested and
analyzed glass microscope slides in a similar manner is indicated on
the graph by a dotted line. The fact that the ultimate strength of the
glass measured in this study differs from the strength as measured by
Mould and Southwick is attributed to different material compositions,
different testing environments, and changes in the method of abrasion.
Since the general relationship between strength and time to failure
appears consistent with earlier studies, the overall difference is
probably unimportant. The standard deviations of the fracture times
are recorded in the last column of Table I. About half of the speci-
mens used in the static fatigue tests were painted in the manner
described for the holographic tests. However, no significant differ-
ences in strength could be noted indicating that the paint had no strength
and/or weakening effects on the fracture strength of the glass specimens.

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The results of the strength measurements taken on the strengthened microscope slides are also summarized in Table I. It can be seen that the chemical strengthening process increases the static fatigue strength of glass by approximately 300-400%. This increase in strength can be attributed to the ability of compressive surface stresses to retard the growth of small cracks at the material surface, thus allowing the glass structure to carry larger loads. Only one constant load level was applied to the specimen since it was found that the large standard deviation of the test results made determination of the time to failure behavior extremely difficult. Tests made at higher loads often caused failure during loading while tests made at lower loads often lasted several days making the taking of data inconvenient.

Attempts were made to holographically monitor failure in these strengthened specimens, but once again the tests proved difficult to perform due to the spread in failure times of the strengthened glass. The standard deviation of the measurements made on the strengthened slides was over 5 hours. This proved to be too high for experimental purposes since too many of the beams failed either before the hologram could be developed or after the average 8-hour observation period. This difficulty was not encountered during tests made on the unstrengthened specimens since the standard deviations of these results ranged from 10 minutes to 1 hour. The means of overcoming this difficulty experimentally are discussed in a later section.

At the present a rigorous analysis has not been formulated of either the interferometric fringe patterns or the material deformations occurring near a flaw in a bending beam. However, certain observations can be made that relate fringe patterns to parameters associated with the propagating flaw in a semi-quantitative manner. The most significant result of these studies is the development of a testing technique that can detect flaws in a failing specimen and allow the experimentor to monitor and even control their propagation. For example, it has been found that it is possible to unload the specimen after the holographic fringe pattern has indicated the existence of a crack that will soon cause failure. Once the specimen is unloaded, the crack propagation is

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arrested and the flaw which was located by the fringe pattern can be viewed microscopically. The crack is most easily observed with a stereo microscope although the exact boundary of the flaw is sometimes difficult to define. A drawing of a typical crack found in this manner is shown in Figure 11. The ability of these holographic observations to locate the precise location of the flaw that causes failure is an important factor of these tests.
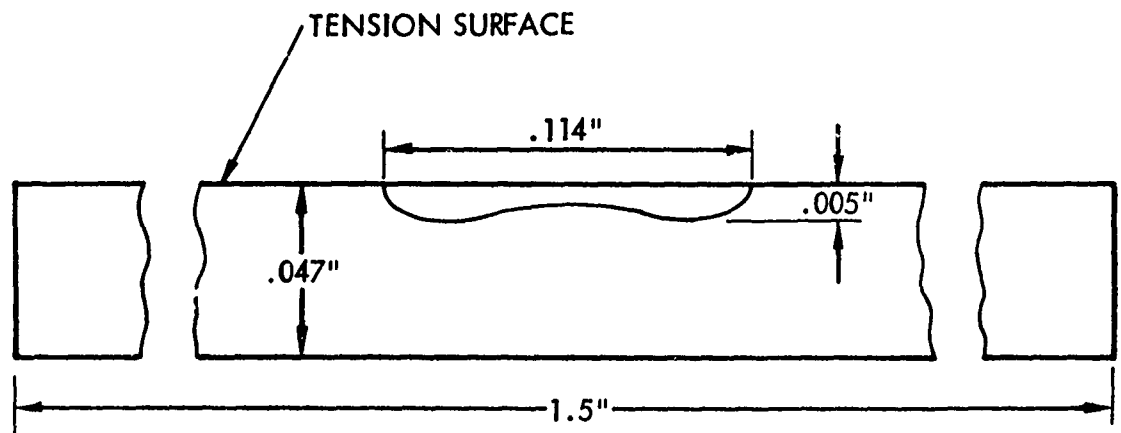

Figure 11. Cross section view of glass specimen showing configuration of crack approximately 2 minutes before failure.

It was assumed earlier in the discussion of the quantitative interpretation of holographic fringes that the deformations occurring during the experiments would be limited to the directions perpendicular to the initial plane of the glass specimen. Analysis of the fringe pattern occurring around propagating cracks in the glass beams tends to validate this assumption. It can be shown using the analysis of Aleksandrov and Bonch-Bruevich (20) that parallax (movement of the fringes across the material surface caused by changes in the viewing angle) observed in an interferogram is evidence of the in-plane strain. The fact that the holographic fringes are not the result of in-plane strain is indicated by the lack of parallax observed when viewing a live fringe hologram formed in these studies.

Since the holographic fringe pattern observed in these experiments is influenced only by out-of-plane deformations, the fringe order n is directly proportional to the deflections of the glass beam. Since

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the elliptical fringes originate at the propagating flaw and move outward across the beam, the highest fringe order n' always occurs at the flaw site. The first fringe order (n=1) was easily identified as the first fringe to develop at the crack. As a result, the fringe patterns shown in Figures 9 and 10 can be considered contour maps of the material surface indicating a slight bulge or hill around the flaw that grew in height as the flaw propagated.

The highest fringe order n' which is plotted along the vertical axis of Figures 12, 13 and 14 is a direct measure of the beam deformation occurring at the location of the propagating flaw. This deflection $W_{n'}$ is computed from the equation

$$W_{n'} = (2n'-1) \ (2.49 \times 10^{-5} \text{ in.}) \qquad 2)$$

where the terms $\sin \theta_1$ and $\sin \theta_r$ of Equation 1 have been determined from the angles of incidence and reflection indicated in Figure 5. The deflection $W_n(x,y)$ occurring at another location of the xy plane of the beam is determined by using the value of the fringe order $n(x,y)$ at that point (x,y) in Equation 2. This is measured by subtracting the number of fringes between the point (x,y) and the crack from the highest fringe order n'. (Identically, $n(x,y)$ can also be determined by counting the number of fringes occurring between the point (x,y) and the location of the 0 order fringe if visible on the specimen.) Since the holograms used in these experiments were formed after the load was applied to the beam, the quantity W_n corresponds to deformation caused by crack propagation and is not the result of changes in the gross applied stress.
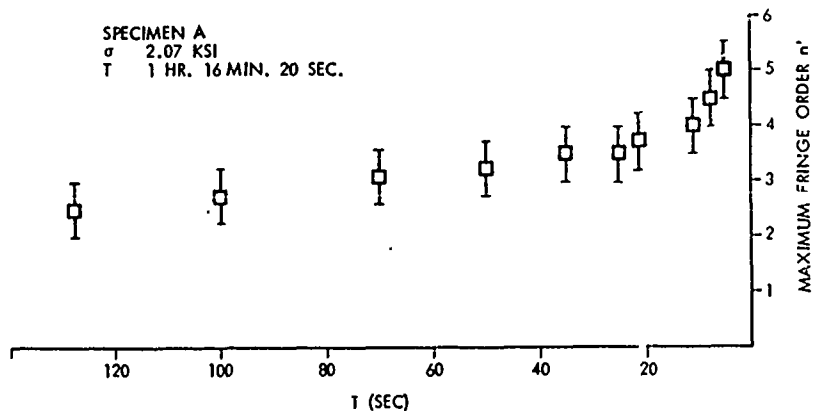

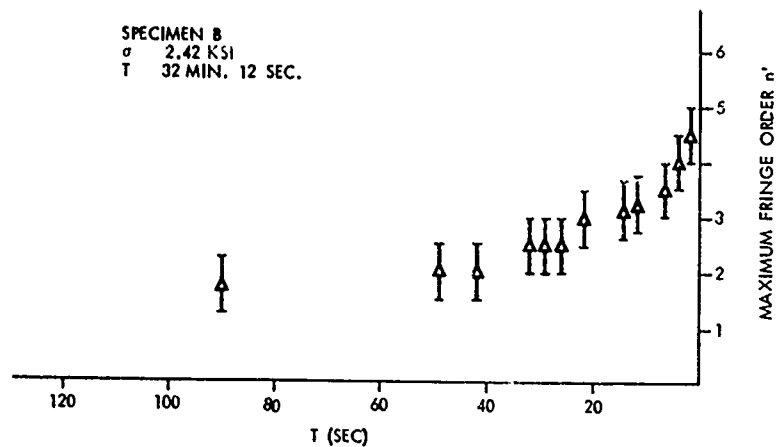Figure 12. Fringe Growth Under Constant Load Versus Time to Failure.

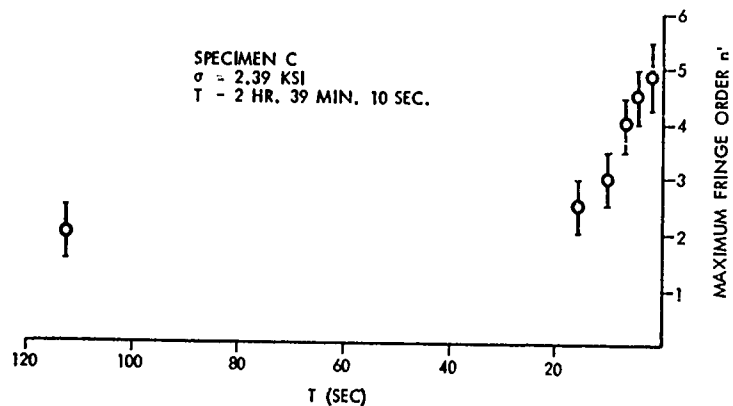Figure 13. Fringe Growth Under Constant Load Versus Time to Failure.

Figure 14. Fringe Growth Under Constant Load Versus Time to Failure.

The increase in the number of fringes as a function of time is caused by the loss of load carrying ability of the glass beam as the area of the crack increases. This has been substantiated by direct microscopic observation of the crack. The rate of fringe growth has been plotted for three tests in Figures 12, 13 and 14 where the quantity n' is the highest fringe order observed at the time t. This number n' is measured by analyzing photographs of the live fringe interferogram and is at least accurate to within ± 1/2 fringe orders. The time t is the time until failure and was recorded automatically in each photograph. The applied stress for each test is also indicated in the Figures.

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The dependence of the growth of holographic fringes with time can be seen in the plot of n' versus log t in Figure 15 where the results of all three tests are indicated on the same graph. This particular form was chosen since the growth of flaws in time has been previously described as exponential (1). The data appears to fall into straight lines with nearly constant slope that tend to permit higher fringe orders and smaller loads where critical flaw lengths are longer. A greater number of tests are needed, however, to more accurately determine the existence and extent of these general relationships.
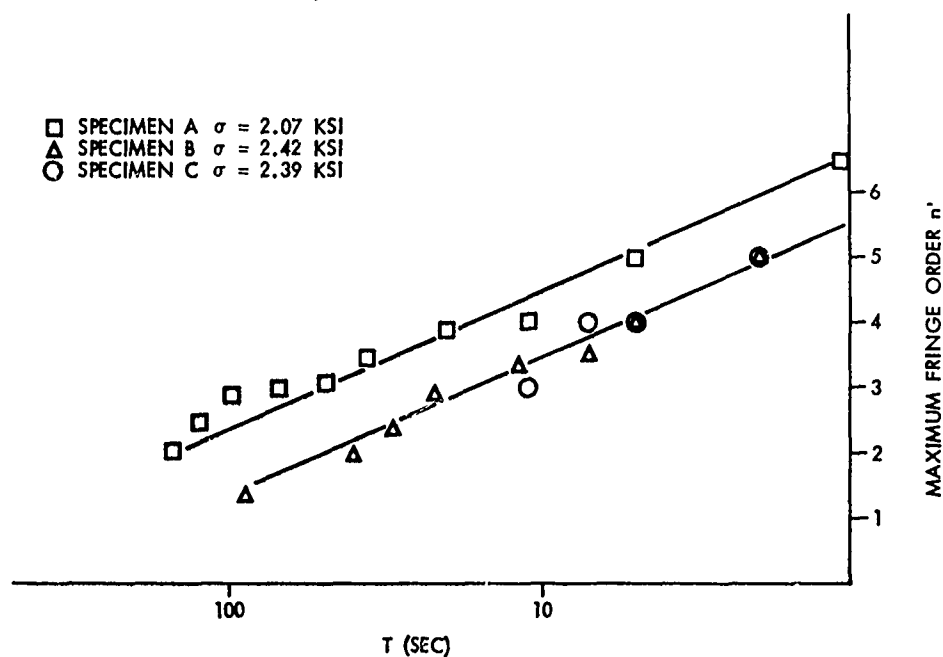

Figure 15. Exponential Fringe Growth Under Constant Load.

During one of the fracture tests which were monitored holographically, two separate cracks were observed propagating at the same time in a single specimen. This phenomenon was indicated by two sets of concentric fringes with a separation between respective centers of about 3.16 in. When both cracks were first observed, they appeared to be propagating in slightly different directions with no interaction of their associated fringe patterns. However, as time progressed, the crack sizes increased and they appeared to bend toward each other. This was evidenced by the interaction and joining of the two fringe patterns. Eventually, the two cracks joined together into a single, but slightly irregular, holographic fringe pattern. The two cracks were first

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observed about 10 minutes before final fracture and appeared to join together about 6 minutes before failure. An obvious irregularity was later observed along the line of fracture at the point where the two cracks had joined.

VIII. CONCLUSIONS

The results of these experiments indicate that holographic inter-
ferometry can be used to detect and locate a flaw propagating in a
stressed material. Although glass was studied in this project, the
above techniques are not restricted solely to brittle materials and can
probably be applied to metals and composite materials. In addition,
some of the restrictions encountered during these experiments were
imposed by the particular equipment used in these studies and are not
indicative of the general potentials of holographic instrumentation and
fracture mechanics. Part I of this program described a highly coherent
pulsed ruby laser system that permits the holographic imaging of large
objects and dynamic events. The techniques used to observe flaws in
this study could be adapted to pulsed ruby instrumentation to permit
direct observation of crack propagation in large objects subject to
dynamic loads.

The use of a photographic plate holder that permits development
of the hologram in its original location could permit the formation of
a hologram in less than a minute. These devices have become commercially
available recently and would significantly increase the flexibility of
the above techniques. By holographically observing a specimen only
minutes after it is loaded, it would be possible to study crack growth
under much higher loads and in materials which have large variations in
test data. Such a capability was found necessary in studying failure
in chemically strengthened glass.

Since holographic interferometry can provide useful qualitative
information as well as sensitive quantitative data, the need for rigorous
fringe analysis varies with the requirements of the problem being
studied. A propagating flaw can be detected and located by simply
observing and locating the characteristic fringe patterns observed in
these studies. This qualitative approach would be most helpful in
studying fracture in irregularly-shaped objects or test specimens that
have complicated strain patterns. By observing these objects with
holographic interferometry, it should be possible to accurately locate

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the failure-producing flaw making accurate determinations of failure producing conditions possible. In addition, weak spots could be determined by the number of flaws occurring at the specific location on the object. Using pulsed ruby holography, these studies could be applied to objects as large as 1000 cubic feet.

The ability of holographic interferometry to determine deformations at all visible points of an object could also prove helpful in the more fundamental studies of crack behavior. By properly designing a laboratory experiment, it may prove possible to rigorously analyze holographic fringe patterns in terms of the three components of material deformation. These deformations occurring near a crack could then be related to crack geometry by the more advanced mathematical models of three-dimensional flaws. Used in this fashion, holographic interferometry would seem to characterize naturally occurring flaws in a multi-dimensional fashion allowing the fracture mechanics investigator to closely study many common assumptions. Problems of interest could include the variations of stress intensity along a flaw border and the interaction of a crack with material irregularities such as voids, fibers, and phase changes. Although these applications would require a degree of sophistication not yet attained, the potentials of holographic interferometry may prove most useful to the study of fracture mechanics.

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