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ARMOUR RESEARCH FOUNDATION  
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ILLINOIS INSTITUTE OF TECHNOLOGY  
Technology Center  
Chicago 16, Illinois

Project No. 90-692J

RESEARCH AND DEVELOPMENT OF LAMINATED  
GLASS AIRCRAFT WINDSHIELDS

Report No. 36

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ARMOUR RESEARCH FOUNDATION OF ILLINOIS INSTITUTE OF TECHNOLOGY

RESEARCH AND DEVELOPMENT OF LAMINATED GLASS AIRCRAFT WINDSHIELDS.

ABSTRACT

This technical report presents a complete summary of the theoretical and experimental efforts which have been directed toward understanding the behavior of special test laminates and laminated windshields subjected to low temperatures (cold-soak conditions).

Good agreement, obtained between theoretical calculations and laboratory experiments, indicates that the deflections and average flexural stresses, produced in a two-ply glass and plastic laminate by a drop in temperature, can readily be predicted.

Although considerable effort has been expended, no theoretical solution has been obtained for the general problem of stresses produced in a three-ply (glass-plastic-glass) laminate subjected to cold-soak conditions. Photoelasticity, the experimental method most applicable for the determination of these stresses, has produced no significant results to date.

The nature, cause, and effect of damage attributable to cold-soak conditions in both aircraft windshields and test laminates have been studied rather extensively; it appears that cold-soak conditions are the most prominent cause of local damage at the interfaces. In general, this damage consists of chipping of the glass and/or delamination between the glass and plastic, both of which may be objectionable in themselves if they become extensive. In many cases, this type of damage may initiate the complete failure of the outer glass pane of the windshield when the windshield is subjected to other stress-producing conditions.

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## RESEARCH AND DEVELOPMENT OF LAMINATED GLASS AIRCRAFT WINDSHIELDS

### I. INTRODUCTION

Certain types of aircraft windshield service failures, together with several preliminary experiments conducted on this Project, had indicated that the polyvinyl butyral plastic interlayer has a decided effect on the behavior of a laminated structure when it is subjected to cold-soak conditions; hence, rather extensive theoretical and experimental work has been devoted to this subject, and the present report represents the status of these efforts as of July 1, 1951.

The term "cold-soak" refers to a condition under which a laminate is subjected to low temperature, usually for extended periods of time. In general, the term implies that the temperature throughout the laminate is uniform at any given time. However, for certain tests described in this report, the definition of the term "cold-soak" is broadened to include cases where temperature gradients exist in the laminate.

At temperatures below 20°F, the linear coefficient of thermal expansion for the plastic interlayer used in aircraft windshields is at least 11 times larger than the linear coefficient of thermal expansion for glass.<sup>1\*</sup> Therefore, when a laminated windshield is subjected to cold-soak conditions, thermal stresses will arise which may cause failure of the windshield or which may contribute to failure in conjunction with other causes such as mechanical loads.

Service failures of laminated windshields have not been described

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\*Superscripts refer to corresponding citations in Bibliography at end of this report.

accurately enough to make it possible to determine the causes of failure. Failures attributed to cold-soak conditions have been observed in standard acceptance tests designed to reproduce actual operating conditions. Resistance to deterioration under a cold-soak test is required by one of the aircraft companies, as follows:

"A cold-soak test shall be conducted at  $-65^{\circ}$  F ambient air for a period of two hours after temperature stabilization has been reached. Defects such as bubbles, separation or small flake chips occurring beyond the trim line of the conductive coating shall not be considered as evidence of deterioration."<sup>2</sup>

A few reports on this type of test, issued by the aircraft companies, indicate that failures of windshields have occurred under such conditions; in fact, frequent failures took place in early tests conducted by these companies.

In an attempt to reduce the number of failures, a parting medium was inserted at the interface of the glass and plastic around the edges of the windshield. Only a few failures due to cold soak conditions have been reported recently, although the difficulty has not been remedied completely.

## II. THEORETICAL ANALYSES TO DETERMINE STRESSES IN LAMINATES SUBJECTED TO COLD-SOAK CONDITIONS

### A. Preface

Considerable time and effort has been expended in an attempt to determine the theoretical stress in a three-ply (glass-plastic-glass) laminate subjected to cold-soak conditions. No valuable analytical solution has been obtained to date, and the concensus is that a theoretical solution of this problem would constitute an analytical program of several years' duration, with doubtful results; accordingly, no further effort will be made in this direction.

A successful analytical investigation has been made of the deflections and flexural stresses in two-ply (glass-plastic) beams and plates subjected to uniform temperature changes. The state of stress at the interface of this two-ply model is now being studied and the results will be presented in a future technical report.

#### B. Deflections and Flexural Stresses in Two-Ply Laminates

An analytical theory which predicts adequately the deflections and average fiber stresses may be borrowed from the theory of bimetallic thermostats. The deflections and average fiber stresses predicted by this theory for two-ply (glass-plastic) beams, simply supported and uniformly heated, are given in Table I. Included also are the results of an extension of the theory of bimetallic strips to include the case of two-ply plates. The development of these equations for both strips and plates is given in Appendix A.

The maximum deflection, as predicted by both the beam and plate theories, is directly proportional to the total thickness of the laminate and the total temperature change and to the square of the span-to-thickness ratio. The deflection depends, in a complicated fashion, on the ratio of glass thickness to plastic thickness; this dependence is presented graphically in Fig. 1. The average fiber stress depends linearly upon the temperature change and, in a complicated relationship, on the ratio of plastic thickness to glass thickness.

### III. EXPERIMENTAL ANALYSIS TO DETERMINE THE STRESSES IN LAMINATES

#### SUBJECTED TO COLD-SOAK CONDITIONS

##### A. Preface

Several cold-soak tests were conducted on two-ply laminates in order to provide an experimental check on the theoretical analyses discussed in

**Table I**  
**DEFLECTION AND FIBER STRESS FORMULAS FOR TWO-PLY LAMINATES**  
**SUBJECTED TO UNIFORM TEMPERATURE CHANGES BELOW 40° F**

Formula	Beam	Plate
Radius of Curvature	$\frac{h}{r\Delta T} = \frac{(0.3504)(10^{-3})}{3 + \frac{(1 + 47.62m^3)(1 + \frac{1}{47.62m})}{(1+m)^2}}$	$\frac{h}{r\Delta T} = \frac{(0.3504)(10^{-3})}{3 + \frac{(1 + 1.283m)}{(1+m)} + \frac{(1 + 37.12m^3)(1 + \frac{1}{37.12m})}{(1+m)^2}}$
Maximum Deflection	$\frac{\delta_{\max}/h}{\Delta T} = \frac{p^2}{8} \left( \frac{h}{r\Delta T} \right)$	$\frac{\delta_{\max}/h}{\Delta T} = \frac{p^2}{8} \left( \frac{h}{r\Delta T} \right)$
Average Fiber Stress	$\frac{\sigma}{\Delta T} = - (12.99)(10^6) \left( \frac{h}{r\Delta T} \right) \left[ \frac{2m^2 + 3m - \frac{1}{47.62m}}{6(1+m)^2} \right]$	$\frac{\sigma}{\Delta T} = - (12.99)(10^6) \left( \frac{h}{r\Delta T} \right) \left[ \frac{2m^2 + 3m - \frac{1}{37.12m}}{6(1+m)^2} \right]$

**NOMENCLATURE**

- h = total thickness of laminate
- m = ratio of glass thickness to plastic thickness
- p = ratio of maximum span to total thickness
- r = radius of curvature
- ΔT = change in temperature from 40° F
- δ<sub>max</sub> = maximum deflection
- σ = average fiber stress on top glass surface

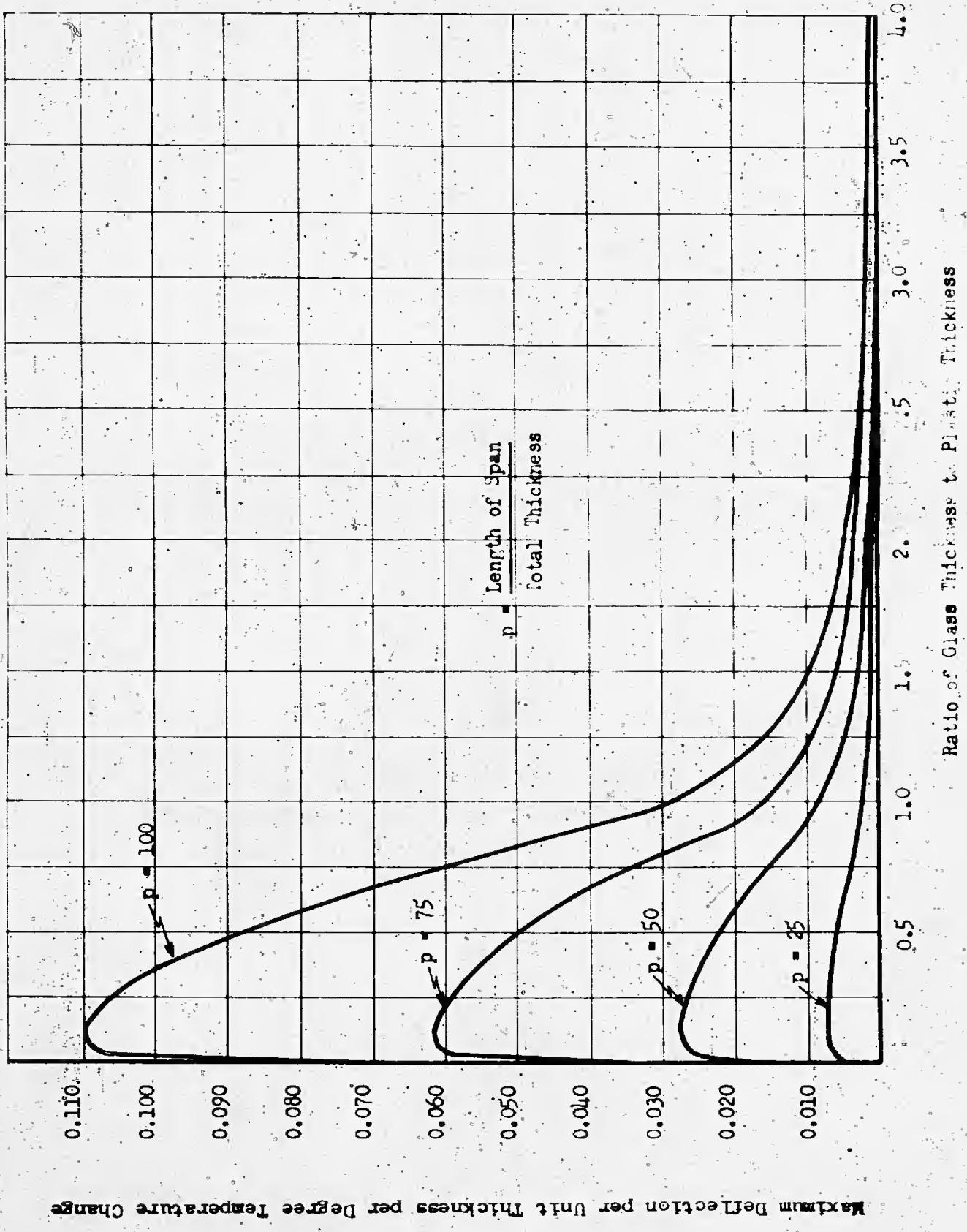


Fig. 1 VARIATION OF MAXIMUM DEFLECTION OF A TWO-PLY S.W.P. SUPPORTED BEAM, WHEN SUBJECTED TO UNIFORM TEMPERATURE CHANGE

Section II. In addition, various methods of experimental stress analysis were considered as a means of providing a solution to the problem of the nature and distribution of the thermal stresses in a three-ply laminate subjected to cold-soak; the use of photoelastic techniques appeared to be the most promising. Photoelastic studies were consequently made on both two- and three-ply laminated models constructed of polished plate glass and polyvinyl butyral plastic.

#### B. Deflections and Flexural Stresses in Two-Ply Laminates

A two-ply (glass-plastic) beam, simply supported at the ends, was placed in an insulated chamber in which a uniform temperature could be maintained by means of a thermostatically controlled hot-cold box. Dial gages and electrical strain gages, mounted at intervals along the top glass surface of the laminate, were used to measure deflections and flexural strains. Thermocouples were placed at various positions on both the top and bottom surfaces of the laminate to measure the temperature of the beam. In the first series of experiments the temperature of the beam was raised to 150° F, and in the second series it was lowered to -35° F. Similar series of experiments were performed on a two-ply laminated plate.

Details of the experimental apparatus and the data obtained are presented in Appendix A. For temperature changes of as much as 100° F, which occurred above 40° F, the strains and deflections observed were negligible. Significant strains and deflections were observed for temperature changes below 40° F, however. The experimental data are summarized in Table II, and are compared with theoretical results based on the equations given in Table I. It can be seen that good agreement exists between experimental and theoretical results.

Table II  
 COMPARISON OF THEORETICAL AND EXPERIMENTAL DEFLECTIONS AND STRESSES IN TWO-PLY LAMINATES  
 SUBJECTED TO UNIFORM TEMPERATURE CHANGE

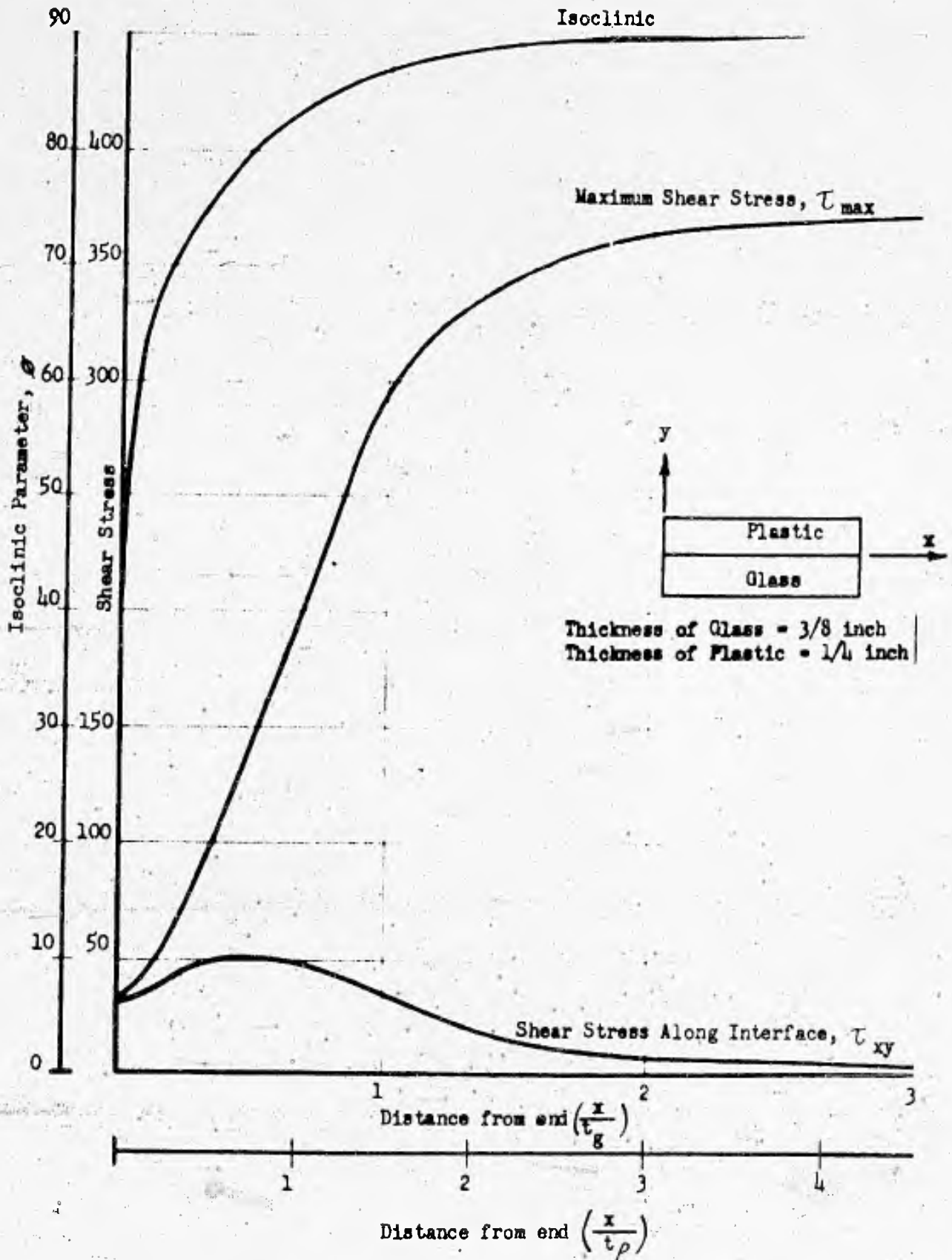
Quantity	<u>Beam</u>		<u>Plate</u>	
	Experimental	Theoretical	Experimental	Theoretical
Maximum deflection per unit thickness of specimen per degree temperature change	0.00563 in/in/°F	0.00595 in/in/°F	0.00879 in/in/°F	0.00985 in/in/°F
Average fiber stress on top glass surface per degree temperature change	28 psi/°F	27.3 psi/°F	50 psi/°F	45.6 psi/°F

	<u>Beam</u>	<u>Plate</u>
Length, in.	20	20
Width, in.	3	12
Thickness of glass, in.	0.1875	0.1875
Thickness of plastic, in.	0.1200	0.1200
Type of mounting	simply supported	pin-supported at corners

### C. Stresses at the Interface of Two- and Three-Ply Laminates

Photoelastic tests have been performed on two- and three-ply beams consisting of glass and plastic laminae of various thicknesses. The beams were placed in an insulated chamber with double glass walls, and the temperature varied slowly so as to maintain the beams at uniform temperature. Polarized light was passed through the beams parallel to their 2-inch dimension and the resulting photoelastic patterns were recorded. In the two-ply beams, it was necessary to lower the temperature of the specimens from room temperature to between 10 and 20° F in order to produce a photoelastic pattern adequate for the determination of stress values. Lower temperatures were used in the case of three-ply beams. Sketches were made of the isochromatics (points of equal maximum shear) and isoclinics (principal stress trajectories); from these experimental data, values of the maximum shear stress were calculated. Appendix B contains a discussion of the test setup and procedure, together with values of the isoclinics parameter, the maximum shear stress, and the shear stress parallel to the interface as observed in a two-ply beam.

Figure 2, which represents the stress distribution in a two-ply beam subjected to low temperatures, shows the maximum shear stress parallel to the interface to have a strikingly low value (50 psi) and to be distributed over a fairly large region near the ends of the beam. These results are puzzling in the light of failures obtained in outwardly identical beams at temperatures which were but a few degrees (10 - 15 degrees) below that maintained during the collection of the photoelastic data. Clearly, the photoelastic results are in error. The error may be attributed to the possibility that in a wide (2. inch) model the directions of the principal stresses in the glass change markedly from plane to plane along the optical axis of the polariscope.



**Fig. 2** ISOCLINIC PARAMETER AND SHEAR STRESS DISTRIBUTION IN TWO-PLY (GLASS-PLASTIC) LAMINATE OBTAINED FROM PHOTOELASTIC TESTS

(Data taken when the beam was at a uniform temperature of  $20^{\circ}$  F. below a  $40^{\circ}$  F. reference temperature.)

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Examination of such a distribution by the techniques of two-dimensional photoelasticity would result in values of stress which are merely "averages" of the true stresses existing across the width of the model.

In photoelastic tests employing three-ply laminates, it was noted that the isoclinics changed position with temperature, and that they became blurred and indistinct in some portions of the beam. Thus, it was necessary to conclude that the directions of the principal stresses do change through the width of the specimen and models as thick as 2 inches in the direction of light propagation cannot be used. The stress distributions obtained in photoelastic tests to date are therefore of questionable significance. Examination of the state of stress existing at the interface of a three-ply laminate subjected to cold-soak conditions will continue on new models more suited to two-dimensional photoelastic techniques.

An indication of the distribution of cold-soak stresses at the center of a three-ply beam can be obtained from photoelastic tests which have been reported previously.<sup>4</sup> The stress distribution at the center of a three-ply beam is essentially uniform. These tests showed compressive stresses in both glass panes of the order of magnitude of 500 psi, with a bending moment of the order of magnitude of 2 to 8 lb-in., when the beam was cooled to -5° F. Considerable differences in the stresses were found in symmetrical and asymmetrical beams. The bending moments were such as to produce concave curvature in the glass panes, the radii of curvature being of the order of magnitude of  $10^5$  ft.

#### IV. PHYSICAL PROPERTIES OF MATERIALS EMPLOYED IN LAMINATED WINDSHIELDS

##### A. Preface

The physical properties which are of interest when considering cold-soak phenomena are: (a) those which have an influence on the stress state produced by cold-soak conditions, and (b) those which determine the conditions under which failure takes place and the manner in which it occurs when a laminate is subjected to cold-soak conditions.

##### B. Properties of Glass and Plastic

The thermal expansivity and modulus of elasticity of annealed glass are quite well known.<sup>5</sup> It appears that the modulus of elasticity of tempered glass differs from that of annealed glass by no more than 5 to 10 per cent. The effect on the stresses of the rate of load application is not known, nor are data available on the stress "memory" of glass, although it seems likely that these effects would be small. The residual stresses in tempered glass have been determined photoelastically<sup>6</sup> and correlated with similar data supplied by the glass companies.

The modulus of elasticity of the plastic as a function of temperature and its thermal expansivity have been determined.<sup>3,1</sup> It is known that the plastic is extremely sensitive to strain rate and that this sensitivity increases sharply with rising temperature; also, there are indications that the plastic has a considerable stress memory.

The non-elastic behavior of the plastic probably is significant because (a) stresses in a laminate may depend on the rate of cooling, and (b) the stress memory of the plastic may result in a dependence of the stress upon previous heating and cooling cycles.

While the elastic properties of glass are quite well known its strength is less well defined, and little is known about its mode of fracture; it is usually assumed that glass fails under tension. Data on failure of glass under shear stresses are not available.

The yield strength and ultimate strength of polyvinyl butyral plastic have been determined under static loading.<sup>3</sup> The effect of previous history is likely to be important, but no information is available on this subject. Only one failure in the plastic caused by cold-soak conditions has been observed.

### C. Properties of the Glass-Plastic Bond

Little is known about the strength of the glass-plastic bond. The strength under the action of shear stresses parallel to the interface may differ from the strength under the action of stresses normal to the interface. In order to obtain data on the strength of a laminate under mechanical loading which produces shear stresses at the glass-plastic interface, tests were performed on three-ply laminated specimens; these tests are described in Appendix C. A thin, circular ring of plastic of varying width was laminated between two glass plates 2-1/2 in. square by 3/16 in. thick. Each plate was held in a square aluminum frame which was placed in a torsion testing machine where an insulated chamber enclosed the specimen. After the temperature of the specimen had been established at a desired value, a torque, which tended to rotate the plates with respect to each other, was applied to the specimens in the plane of the glass. It was hoped that this test would produce torsional shear failure at the glass-plastic interface. In the course of the test, the load increased steadily until failure of the specimen occurred, at which time

the load suddenly decreased. The applied torque was read on a dial and the load failure was recorded. Examination of the failed specimens disclosed chipping-type failures in the glass in the area of the glass-plastic bond. The shear stress at failure, at the outermost fiber of the ring-shaped bonded area, varied between 1200 and 2800 psi for the six specimens tested. The magnitude of the maximum tensile stress in the glass at the interface where failures occurred was thus less than 50 percent of the accepted tensile strength of glass. In addition to the chipping failures, however, the specimens showed cracks through the thickness of the glass panes extending inward from the edge of the panes. These cracks indicated that stress concentrations may have been present at the edges where the specimens were held in the frames; hence, the significance of the results is questionable.

There is some evidence that a weak glass-plastic bond (such as that obtained by gluing with Duco Cement) produces local damage in the glass at the interface.<sup>7</sup> Previous tests revealed that very little slippage occurred at the bonded interface when the plastic underwent volumetric expansion due to heating. In the theoretical treatment of the problem, it was assumed that no slippage occurs at the interface so that perfect continuity exists between glass and plastic. There is also evidence that the conductive coating affects the strength of the bond.

#### D. Properties and Effect of Conductive Coating

The conductive coating is a layer of tin oxide of molecular dimensions. Thermal failure tests of sample laminates indicate that the strength of this layer affects the strength of the laminate.

The difference in thermal expansivities of the conductive

coating and the glass may cause stresses in the coating. Little is known about the strength of the coating; however, there is evidence that it has considerable abrasive strength.<sup>8</sup> Damage to the coating has been observed as follows: (1) in reports from the aircraft companies and in tests on full-sized windshields with a conductive coating, discolored areas with a web-like texture were observed near the edges, suggesting tensile failure of the film in a direction parallel to the interface; and (2) in failure tests on full-sized windshields conducted by Boeing Aircraft Co., and in failure tests on small beams in the ARF laboratory, patches of film were observed on both glass and plastic at the interface after delamination, indicating that the film had been pulled off the glass. The patches of film as such showed no damage.

#### V. FAILURES OF LAMINATED WINDSHIELDS AND TEST LAMINATES SUBJECTED TO COLD-SOAK CONDITIONS

##### A. Preface

Qualitative information on the strength of laminates, the possible effect of various factors on their strength, and their mechanism of failure has been discussed in several sections of this report. The objective of this section is to summarize the results of cold-soak tests conducted under laboratory conditions and relate them to failures incurred under service conditions. Generally, the effect of cold-soak stresses becomes evident only when the laminate develops failures. This, coupled with the statistical failure characteristics of glass and complicating factors, such as variability of bond and conductive film strength, makes the interpretation of experiments difficult.

## B. Failures of Laminated Windshields

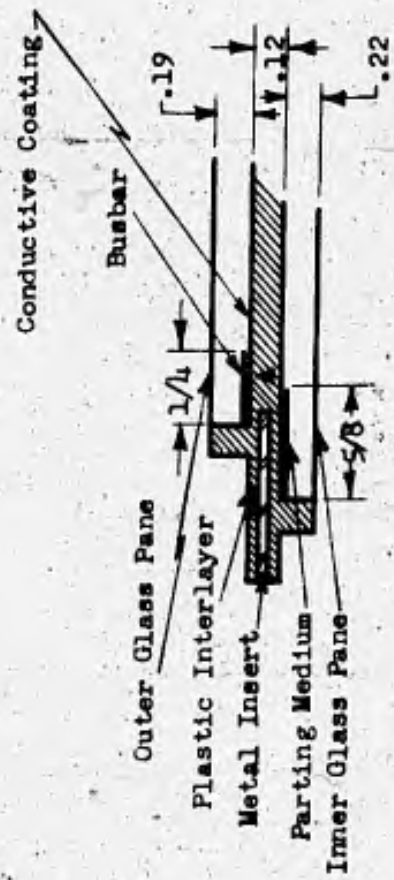
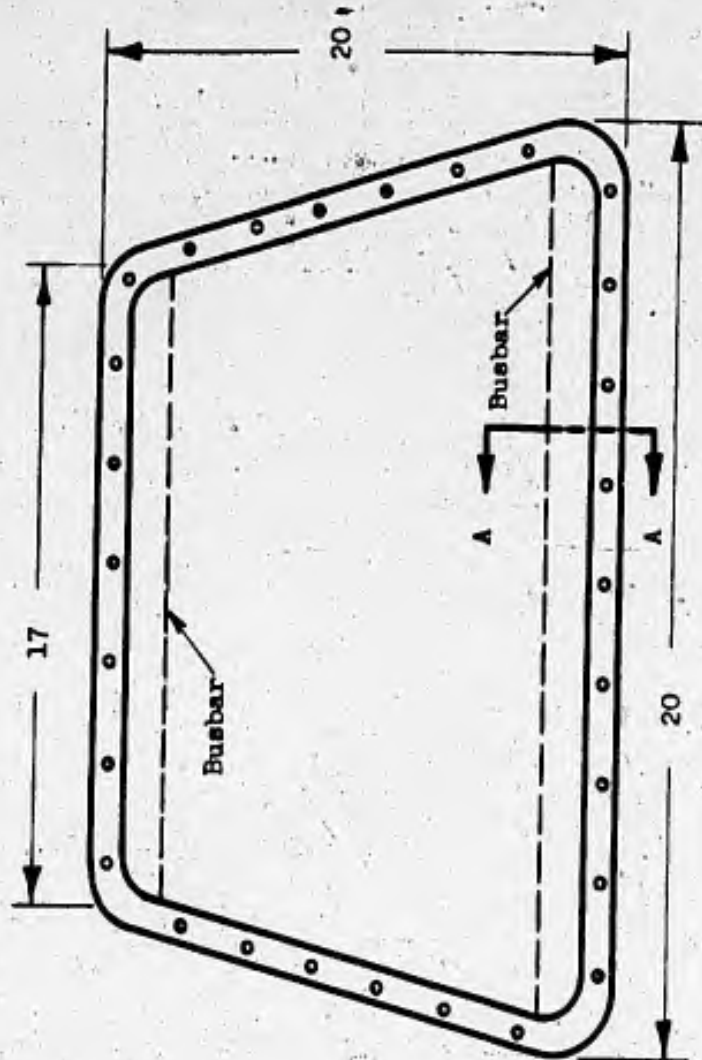
Most windshields which contain an electrically conductive coating at the inner surface of the outer pane are flat and trapezoidal in shape. Features of construction and approximate dimensions of such a windshield are illustrated in Fig. 3; in many respects, this windshield is typical of the electrically heated windshields now in service.

Cold-soak service failures occur in windshields at low temperatures with the film power off; cold-soak stresses may contribute to failures under other conditions. Generally, cold-soak damage occurs at the interface of the laminate. The meager amount of available information on service failures under various conditions has, for the most part, been supplied by the aircraft manufacturers. The most significant portions of this information are given here.

One of the aircraft companies indicates that the following types of service and test failures have been observed:<sup>9</sup>

1. Failure under pressure alone (outer pane fails first).
2. Failure under application of heat alone. Failure of outer pane results from (a) hot spots near the edge of the windshield, (b) bus bar failure, leading to local hot spots, and (c) failures of coating due to delamination, with outer pane sometimes failing as a result of hot spots produced in the area of delamination.
3. Failures resulting from various combinations of pressure and heat.
4. Delamination and edge chipping produced by extreme cold-soak tests at  $-65^{\circ}\text{F}$ .

The fourth type of failure is naturally of most interest in this discussion.



Section AA

Fig. 3 TYPICAL FEATURES AND DIMENSIONS OF A COMMERCIAL, THREE-PLY, ELECTRICALLY HEATED WINDSHIELD

- Notes: (1) Parting Media usually optional with Windshield Manufacturers  
 (2) All glass edges beveled.

In another report on service failures of windshields, damaged windshields are described as follows:<sup>10</sup>

Approximately two-thirds of 30 windshields which were examined failed at the bus bar. Failures of this type were about equally divided between breaks in the lead from terminal to bus and breaks in the connection between bus and conductive coating. The first type of failure was evidenced by non-heating of the windshields, while the second was accompanied by arcing which progressed to form objectionable delamination and caused cracking of the outer pane in one or two instances. Two of these failures were actual breaks of the bus bars. This type of failure at the bus bars was about equally distributed between upper and lower bus bars.

All of the remaining windshields, except one, were removed from service because of delamination. These delaminations occurred, for the most part, at the lower corners between the plastic and the outer pane and were not accompanied by glass chipping. The delamination was considered too severe when it extended about 1-1/2 in. into the windshield from the edge. The remaining windshield had a shattered inner pane. The break started near the upper edge, a little outboard of center, and cracks extended radially across the entire pane. No reason for such a break could be given.

A staff member of an aircraft company stated that, "vinyl stress caused by cold-soak is applied largely to the edges and the use of the parting medium has been found to be quite effective in eliminating glass edge chipping at low temperatures. The delamination problem, as related to parting media, requires additional study, but in the meantime it is felt to be most essential to eliminate glass edge chipping on windshields in service."<sup>11</sup>

In an aircraft company test report, the following results are presented:<sup>12</sup>

With the exception of glass breakage, the most important type of deterioration in electrically heated windshields is delamination. The delamination may take the form of a separation occurring either between the vinyl interlayer and the conductive coating, or between the conductive coating and the glass. In the laboratory, delamination has occurred frequently in the windshields which have been left over night following a series

of heat and pressure tests. Delaminations have occurred in service in electrically heated windshields of all types. Some windshields are subject to minor delaminations extending inward from the edge of the outer pane or edge of the bus bar about 1/16 to 1/8 in. These delaminations, as a rule, leave the conductive coating intact and, therefore, are objectionable only optically. Other windshields are subject to delaminations which may extend from one to several inches inward from the edge or corner of the outer pane. These large delaminations frequently break the conductive coating, creating a cold spot with adjacent hot spots. The high thermal stresses which result invariably lead to failure of the glass. The causes of delamination have not been obvious; however, it has been noted that in the majority of cases, the delaminations have occurred at or near the edge or tip of the bus, places which have been found frequently to be hot spots. An experiment to investigate the relationship between delamination and hot spots is therefore in order.

Comparatively few reports are available on cold-soak tests, as such; however, three reports have been obtained which relate directly to this subject. Results are recorded as follows:

An electrically heated windshield was subjected to cold-soak at  $-65^{\circ}\text{F}$ .<sup>13</sup> The test resulted in some delamination at the upper and lower edges of the outer pane and some delamination extending inward from the parting medium around the inner pane.

Three windshields with 13/64-in. outer panes and a parting medium at the outer pane were subjected to cold-soak tests at  $-65^{\circ}\text{F}$ .<sup>14</sup> Two of the windshields developed chipping at the interface near the inner pane. Damage did not extend beyond the trim line.

Seven windshields were subjected to cold-soak tests at  $-50^{\circ}\text{F}$ .<sup>15</sup> Inner pane chipping and chipping and delamination along the bus bars were produced. The test also produced delaminations at random in the outer pane, pulling the conductive coating from the glass.

Summarizing, it is evident from the reports discussed that (1) failure generally consists of either (2) breakage of the outer pane, or

(b) local damage which occurs at the interface of either the outer pane or the inner pane near the edge of the windshields; and (2) local damage, particularly bus bar failure or damage to the conductive coating, is objectionable in itself if it is extensive; in addition, it may contribute to or cause failure of the outer pane since it tends to create hot spots. The following types of local damage have been reported:

1. Delamination (separation of glass and plastic at the interface). Separation of glass and plastic occurs at the interface of the inner pane (not coated). At the interface of the outer pane (conductive coated), the coating may adhere to either the glass or the plastic in the course of delamination. Various tests indicate that a delamination which does not affect the conductive coating does not produce a fracture in the outer pane, while a delamination which is accompanied by a break in the conductive coating frequently produces such a fracture. In most instances, such fractures occurred while power was being applied to the coating, so that fractures may have been produced by hot spots. Delaminations which did not affect the conductive coating occurred frequently while the power to the coating was turned on, the plastic being warm and soft. Delamination under cold-soak conditions (without power to the coating and with the plastic cold) usually led to damage of the coating. Delamination occurred most frequently at the interface near the coated (outer) pane, and sometimes from the edge of the parting medium at the inner pane.

2. Chipping of the glass. This type of failure occurred

most frequently at the edges of the inner pane where no parting medium was used, or where the parting medium was inadequate or suffered from various imperfections. Extensive chipping also occurred at the edges of the bus bars in the outer pane. Cracks in the glass occurred at areas of delamination, particularly when hot spots were present.

3. Bus bar failures. Bus bars failed by separation from the glass or because of flexing at the terminals.

The damage described above occurred both in service and during various tests. Many of these tests consisted of cooling and warm-up cycles of the windshields with application of pressure and power to the coating in accordance with certain schedules; others were pressure tests, cold-soak tests, or various special tests. There is no evidence that cold-soak stresses alone caused breakage of the glass, other than chipping at the interface, in commercial windshields. No cracking of the outer pane under cold-soak conditions has been reported; however, cold-soak conditions are the most evident cause of high stresses at the interface and, therefore, may be a major cause of damage.

#### C. Failures of Test Laminates

Three series of cold-soak tests, which are discussed in Appendix D, were conducted in an effort to better understand the behavior and mechanism of failure of three-ply (glass-plastic-glass) laminates subjected to cold-soak conditions. These tests were initiated to study the conditions under which damage to the test specimens occurred, the damage suffered as a function of test specimen construction, and the resulting failures.

In order to study the effect of specimen construction on damage suffered, a number of specimens of various designs were tested. The test specimens were two- and three-ply, 2 by 12 in. laminated beams, which were either supplied by the glass companies or laminated in the laboratory autoclave. The various types of three-ply beams tested were:

1. Two annealed glass panes of various thicknesses and a plastic interlayer of constant thickness.
2. Two 13/64-in. thick annealed glass panes and a plastic interlayer of variable thickness (laminated in the laboratory autoclave).
3. One annealed and one tempered glass pane in several thickness combinations, with plastic interlayer.
4. One conductive coated pane and one annealed glass pane, of different thickness, with plastic interlayer.

Three series of tests were performed in which the cooling rate varied from an average of 7 F. per hour to the very rapid cooling obtained by quenching in cold alcohol. The damage suffered by the beams was studied carefully and recorded; in several cases, photographs were taken of the damaged specimens.

Two-ply beams failed in about the same temperature ranges as observed in the deflection tests of two-ply beams which are described in Appendix A of this report. With one exception, no damage occurred in any of the three-ply beams when subjected to slow uniform temperature changes.

Damage was produced in three-ply laminates by quenching in cold alcohol. As discussed in Appendix D, the stresses causing failure in these tests probably were cold-soak stresses, applied at a higher strain rate

than in the slow uniform cooling tests.

In general, damage was first observed after quenching to about -80 F. Among the three-ply beams provided by the glass companies, those without conductive coating at the interface developed only local damage in the course of the tests. Three-ply beams containing a conductive coating at the interface failed by shattering of the coated pane and separation of the plastic from the other pane due to chipping in the glass parallel and close to the interface. Similar failures occurred in ARF laminated three-ply beams made with two tempered panes.

Nearly all the local damage observed consisted of chipping or cracks in the glass which began at the interface. Most of the cracks began at or near the edge, frequently on the beveled portion of the edge. In the three-ply beams, complete separation due to chipping occurred in the pane opposite the filmed pane; however, part of the glass interface near the edges was frequently undamaged, indicating delamination. Extensive areas of delamination were observed in the two-ply beams made with filmed glass panes. Only small areas of delamination were observed in two-ply beams constructed with tempered or annealed glass panes.

Prior to complete failure of the beam, comparatively little local damage at the edges occurred in three-ply beams which had a conductive coating at an interface; however, discolored spots at the interior of the beam were observed before failure occurred. These spots probably indicated delamination which may have included damage to the conductive coating. Inspection of the interface after failure indicated that most of the conductive coating adhered to the glass, with the exception of a few spots in the interior of the beam where the coating remained

with the plastic. There was some evidence that delamination occurred at the interface containing the conductive coating. In all instances, extensive chipping in the glass occurred under the bus bars.

Among three-ply beams laminated in the autoclave, those composed of two tempered panes and those containing a conductive coating at an interface failed by disintegration of the glass. The other beams, with two probably insignificant exceptions, developed local damage only. Generally, local damage in these beams was more extensive than that observed in commercially prepared beams, partly due to the fact that ARF laminated beams were constructed with square edges. Fragments of the shattered tempered (filmed) glass pane fell off the plastic at the interface. The failure tests also disclosed the fact that in most cases edge chipping was reduced by alcohol attack softening the plastic.

Beams composed of one annealed pane and one fully tempered pane suffered more damage in the annealed pane than beams containing two annealed panes. Only slight damage occurred in the tempered pane of such beams. It was not possible to determine the effect of the relative thicknesses of the glass panes on the damage suffered by the beams. Damage to the plastic in the form of a transverse fracture was observed in only one instance.

The results of these tests may be interpreted as follows:

1. The fact that two-ply beams failed under uniform cold-soak conditions, while three-ply beams developed no damage except when quenched in cold alcohol, indicates either (a) that the stresses at the interface in three-ply beams differ from those in two-ply beams, or (b) that the stresses at the interface changed due to the deflection of two-ply beams.

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2. The consistent failure of beams made with a filmed surface at the interface indicates that the conductive coating either (a) affects the strength of the bond, or (b) influences the stress state in the glass next to the interface. Experiments indicate that the strength of the bond is reduced.

3. The most extensive areas of delamination were observed in two- and three-ply beams with a conductive coating at an interface. This shows that delamination takes place more easily at an interface next to a conductive coating; this conclusion is corroborated by the fact that delamination in commercial windshields occurs most frequently next to the outer pane, which has a conductive coating.

4. The fact that beams laminated in the laboratory developed more edge cracks than commercially prepared beams indicates that the extent of edge chipping depends largely on the condition of the glass edge; however, it also was evident that a multitude of edge cracks did not, as a rule, develop into more extensive damage at the edges, nor did they produce complete failure of the glass panes.

5. The fact that nearly all local damage in the glass occurred at the edges indicates a high concentration of tensile stresses in the glass very near the edges. The appearance of the fractures indicates that tensile stresses nearly perpendicular to the interface were the cause of these failures.

6. The fact that chipping occurred in glass which was not filmed agrees with the occurrence of chipping at the inner

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pane and the absence of chipping in the outer pane of commercially prepared windshields, except near the bus bars. Chipping underneath the bus bars in the test laminates agrees with the occurrence of chipping at and near the bus bars in the outer pane of service windshields.

7. It was not possible to determine whether the stresses causing delamination were of the same nature as the stresses producing failure in the glass.

## VI. CONCLUSIONS

Cold-soak stresses have their largest value at the interface of glass and plastic where they appear to be the most prominent cause of damage. Damage under cold-soak conditions has been observed in aircraft windshields, although the use of a parting medium has overcome this difficulty to a certain extent. Damage at the interface in service and in the course of various laboratory experiments has been observed frequently and may be due also to cold-soak stresses or stresses with similar action.

The analytical study of stresses at the interface of the laminate is an extremely complicated problem whose solution has not been achieved.

Several methods of experimental stress analysis have been considered as a solution to the problem of determining the nature of cold-soak stresses in laminates. The photoelastic technique was found most readily applicable; however, little success has been achieved with this method to date.

The nature, cause, and effect of damage under cold-soak conditions have been studied. Cold-soak damage consists of damage at or near the interface. No breakage, other than chipping, of laminated glass windshields under cold-soak conditions has been reported, although such failures have been produced

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on small beams in the laboratory. Interface damage is objectionable as such and frequently is a contributory cause of outer pane breakage.

Consideration of the viscous nature of the plastic indicates that cold-soak stresses depend on the cooling rate and the sequence of loading cycles and, therefore, are not strictly an elastic problem. Failures under cold-soak conditions depend on the properties of glass and plastic, the strength of the glass-plastic bond, and the effect of the conductive coating; information on these properties is limited.

Damage in cold-soak tests conducted by the aircraft companies has been studied and some correlation with damage under other test conditions has been established. Cold-soak tests of small laminated beams have been performed in the laboratory; these tests yielded some information on the effect of the design of a laminate on its resistance to failure and on the conditions under which failure occurred. The nature of the damage in small beams was similar to that observed in tests conducted on windshields by the aircraft companies.

#### VII. CONTRIBUTING PERSONNEL

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APPENDIX A  
THE BEHAVIOR OF  
TWO-PLY (GLASS-PLASTIC) LAMINATES  
SUBJECTED TO UNIFORM TEMPERATURE CHANGES

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## APPENDIX A

### THE BEHAVIOR OF TWO-PLY (GLASS-PLASTIC) LAMINATES

#### SUBJECTED TO UNIFORM TEMPERATURE CHANGES

##### I. INTRODUCTION

The bending properties of two-ply (glass-plastic) laminates subjected to uniform temperature changes were studied experimentally by placing test specimens in a thermostatically controlled air chamber and measuring deflections and flexural strains with dial gages and electrical resistance strain gages.

The experimental data were compared with the analytical theory for two-ply laminated beams, developed by S. Timoshenko\* for application to bimetallic thermostats, and with extensions of this theory to laminated plates.

Glass failures which occurred in low temperature ranges were studied with the aid of a photographic technique for examining the fracture surfaces.

##### II. EXPERIMENTAL MEASUREMENTS OF DEFLECTIONS AND FLEXURAL STRAINS

###### A. Description of Apparatus

All uniform temperature tests were performed in a 12-cubic foot, constant-temperature chamber made of Celotex and fitted with double-pane observation windows (see Fig. A-1).

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\*S. Timoshenko, "Analysis of Bimetal Thermostats", Journal of the Optical Society of America, II (Sept. 1925), 233-255.

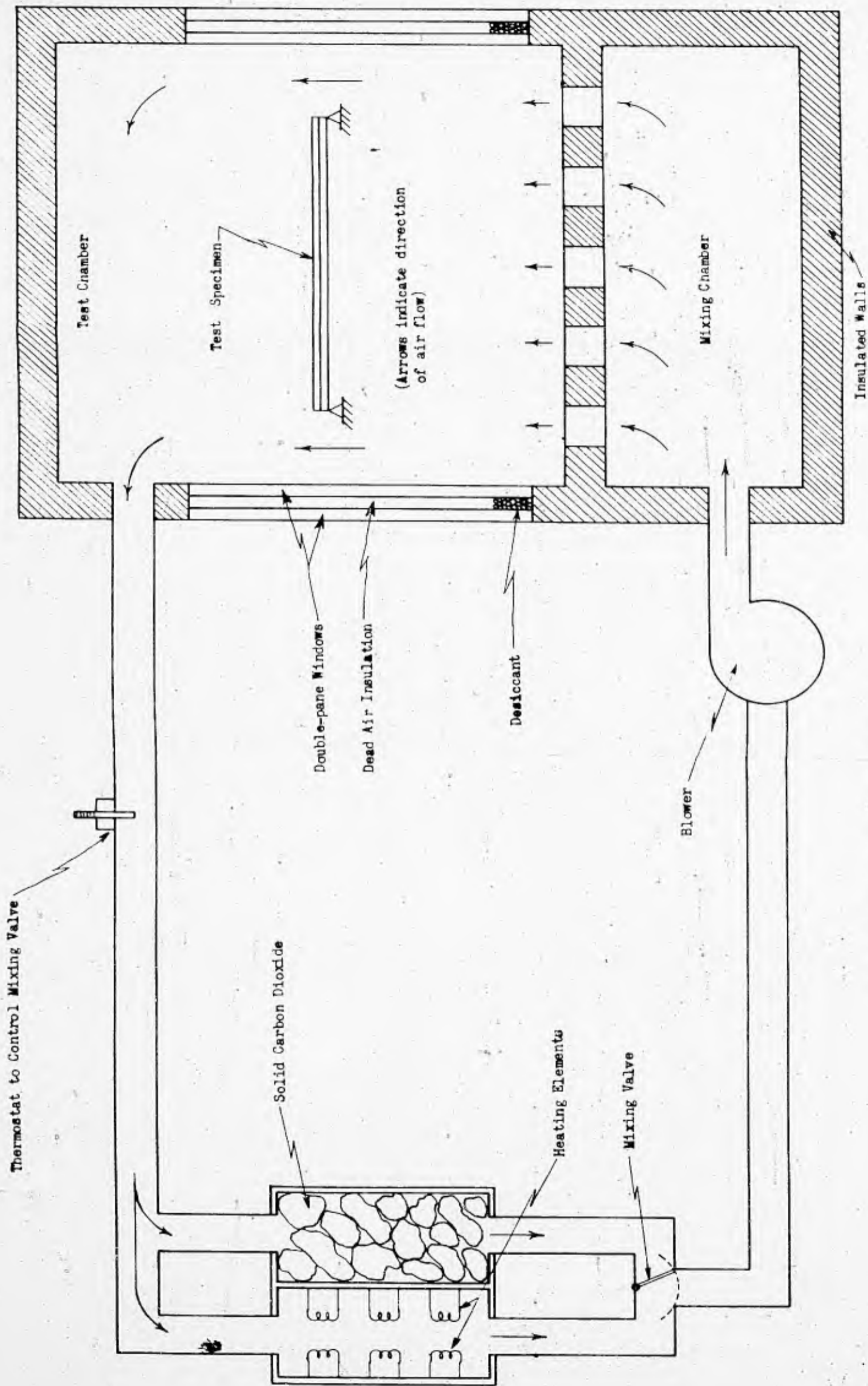


FIG. A-1 CONSTANT-TEMPERATURE CHAMBER

Air, circulated through the test chamber by means of an electrically driven blower, served as the heat transfer medium. Desired test temperatures were obtained by means of a thermostatically controlled mixing valve which appropriately directed the air over either a tray containing broken pieces of carbon dioxide (dry ice), or series of electric heating elements.

Experiments were performed on three different specimens, the dimensions and mounting conditions of which are summarized in Table A-1.

Several preliminary experiments were performed on a single glass pane (Specimen No. 3) with temperature changes from 60° F to 150° F and from 60° F to 0° F to measure the temperature stability of the test chamber and to determine the corrections needed in two-ply, experimental results to compensate for thermal strains in the dial gages and gage supports. Measurements at various points in the chamber indicated that temperatures on the same horizontal plane would vary less than  $\pm 1^\circ$  F. The corrections in dial gage readings caused by thermal contractions or elongations of the dial gages and gage supports amounted to less than 0.0005 inch for the maximum temperature change recorded.

SR-4, Type A-1 electrical strain gages were placed at intervals along the top glass surface of the laminates to measure flexural strains, dial gages\* were mounted above the beam to measure deflections, and thermocouples\*\* were placed in various positions on both the top and

---

\*One-inch travel, 0.001-in. Federal Dial Gages.

\*\*Iron-constantan junction soldered to a copper foil button cemented to the surface of the laminate with sodium silicate (water glass).

Table A-I  
SPECIMENS USED IN UNIFORM TEMPERATURE CHANGE TESTS

Identification	Specimen No. 1	Specimen No. 2	Specimen No. 3
Description	Two-ply (glass-plastic)	Two-ply (glass-plastic)	Single glass pane
Type of mounting	Simply-supported beam	Plate, pin-supported at corners	Plate, pin-supported at corners
Length	20 in.	20 in.	20 in.
Width	3 in.	12 in.	12 in.
Thickness of glass	0.1875 in.	0.1875 in.	0.2031 in.
Thickness of plastic	0.120 in.	0.120 in.	—
Source	Sawed from 12-by-20-in. plate laminated by Pittsburgh Plate Glass Co.	Pittsburgh Plate Glass Co.	Pittsburgh Plate Glass Co.

bottom surfaces of the laminates to measure temperature. In all experiments, the dial gages were mounted on Invar supports.\*

Strain gage readings (microinches per inch) were obtained from a Baldwin SR-4, Model K, Strain Indicator. Temperature compensation was obtained by using a dummy gage mounted on a single glass pane located in the test chamber as one of the reference arms of the indicator's Wheatstone bridge; thus, the strains measured are those due only to bonding resulting from the difference between the coefficients of expansion of the glass and plastic.

Millivolt readings, obtained from a Leeds and Northrup Potentiometer (using a 32° F water-ice reference junction), were converted to Fahrenheit temperature measurements with the aid of standard conversion tables provided by the potentiometer manufacturers.

#### B. Experiments with Two-Fly (Glass-Plastic) Beam (Specimen No. 1)

The laminated beam (Specimen No. 1) was simply supported on round rods, with gages and thermocouples located as shown in Fig. A-2.

The beam was placed in the insulated chamber at room temperature, and then the temperature of the chamber was gradually lowered to -35° F. Negligible strains and deflections were observed above 40° F, but below 40° F they became comparatively large. Table A-II summarizes the experimental data. The average temperature of the beam represents the average of five thermocouple readings on both the top and bottom surfaces of the specimen and two thermocouple readings in the vicinity of the dummy strain gage. The temperature varied less than  $\pm 1^\circ$  F.

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\*Invar is an iron-nickel alloy with the low thermal coefficient of linear expansion of  $0.8 \times 10^{-6}$  (in/in)/°F.

□ Strain Gage

+ Vertical Deflection Measured with Dial Gage at This Point

⊗ Thermocouple on Top Surface of Glass

○ Thermocouples on Top Surface of Glass and on Bottom Surface of Plastic

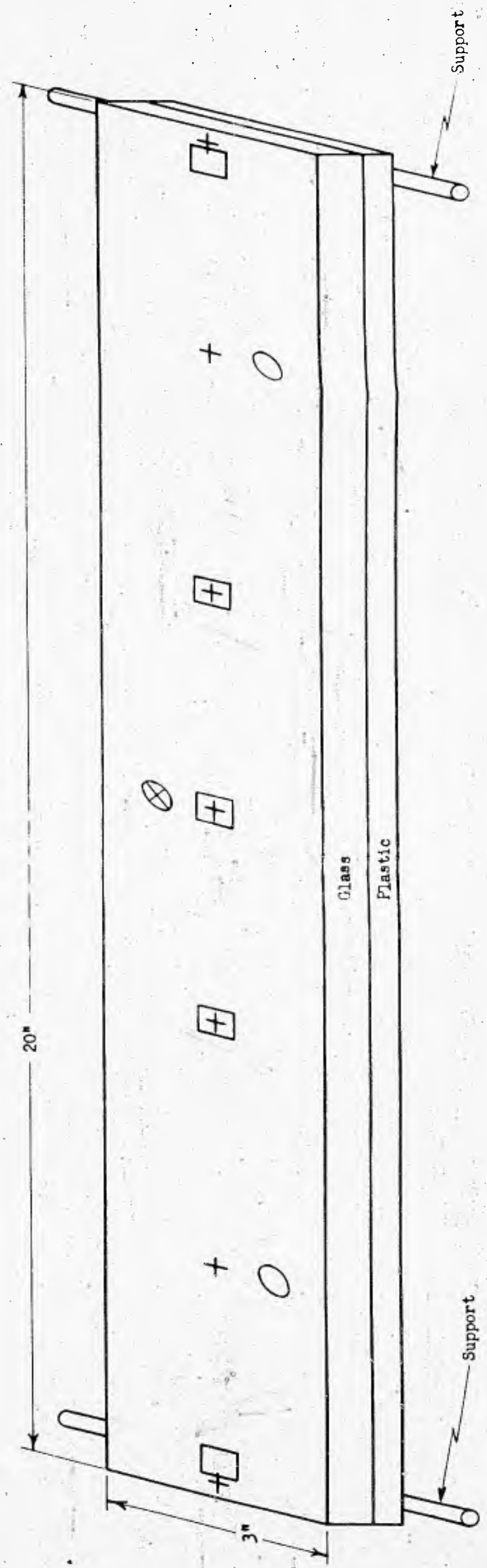
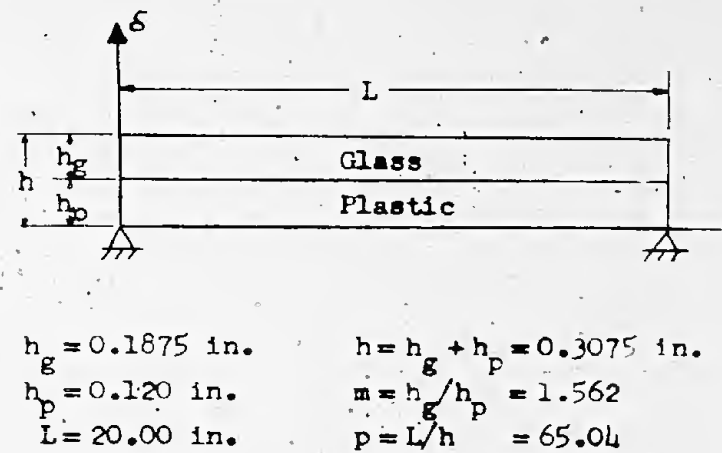


FIG. A-2 LOCATION OF MEASURING INSTRUMENTS ON TWO-PLY (GLASS-PLASTIC) BEAM (SPECIMEN NO. 1)

**Table A-II**  
**STRESS AND DEFLECTION OF A TWO-PLY (GLASS-PLASTIC) LAMINATED BEAM (SPECIMEN NO. 1)**  
**SUBJECTED TO A UNIFORM TEMPERATURE CHANGE BELOW 40° F**

Reading No.	Time from Beginning of Test min	Average Temperature of Beam		Change in Temperature (a) °F	Average (b) Observed Deflection, $\delta$				
		Potentiometer Reading mv	Temperature °F		$\bar{x}=0$	$\bar{x}=0.115$	$\bar{x}=0.244$	$\bar{x}=0.369$	$\bar{x}=0.500$
					in.	in.	in.	in.	in.
1	0	+ 1.03	+ 67.6	—	0	0	0	0	0
2	30	- 1.27	- 13.0	- 53.0	- 0.0019	+ 0.0335	+ 0.0628	+ 0.0801	+ 0.0858
3	45	- 1.45	- 19.8	- 59.8	- 0.0049	+ 0.0411	+ 0.0756	+ 0.0965	+ 0.1030
4	60	- 1.54	- 23.3	- 63.3	- 0.0049	+ 0.0419	+ 0.0771	+ 0.0985	+ 0.1052
5	75	- 1.58	- 24.7	- 64.7	- 0.0051	+ 0.0425	+ 0.0783	+ 0.1001	+ 0.1072
6(c)	105	- 1.83	- 34.2	- 74.2	- 0.0063	+ 0.0444	+ 0.0830	+ 0.1054	+ 0.1122

Reading No.	Normalized Deflections, (d) $(\delta/h) \Delta T$				
	$\bar{x}=0$	$\bar{x}=0.115$	$\bar{x}=0.244$	$\bar{x}=0.369$	$\bar{x}=0.500$
	(in/in)/°F	(in/in)/°F	(in/in)/°F	(in/in)/°F	(in/in)/°F
1	—	—	—	—	—
2	0	0.0022	0.0040	0.0051	0.0054
3	0	0.0025	0.0044	0.0055	0.0059
4	0	0.0021	0.0042	0.0054	0.0057
5	0	0.0024	0.0042	0.0053	0.0057
6(c)	0	0.0022	0.0040	0.0050	0.0053



Reading No.	Average Flexural Strain, $\epsilon$ , on Top Surface of Glass			Flexural Stress, $\sigma$ , on Top Glass Surface			$\sigma/\Delta T$		
	$\bar{x}=0.007$	$\bar{x}=0.246$	$\bar{x}=0.500$	$\bar{x}=0.007$	$\bar{x}=0.246$	$\bar{x}=0.500$	$\bar{x}=0.007$	$\bar{x}=0.246$	$\bar{x}=0.500$
	$\mu$ in/in	$\mu$ in/in <sup>(2)</sup>	$\mu$ in/in	psi	psi	psi	psi/°F	psi/°F	psi/°F
1	0	0	0	0	0	0	—	—	—
2	71	138	143	710	1380	1430	13.40	26.04	26.98
3	138	175	203	1380	1750	2030	23.08	29.26	33.95
4	149	—	—	1490	—	—	23.54	—	—
5	149	171	209	1490	1710	2090	23.03	26.43	32.30
6(c)	181	191	226	1810	1910	2260	24.39	25.74	30.46

**NOMENCLATURE**

$e$  = flexural strain at top glass surface  
 $h_p$  = thickness of plastic layer  
 $L$  = length of beam  
 $p = L/h$  = shape ratio  
 $x$  = distance measured along beam  
 $\delta$  = deflection of beam  
 $h_g$  = thickness of glass layer  
 $h = h_p + h_g$  = total thickness of beam  
 $m = h_g/h_p$  = thickness ratio  
 $\Delta T$  = change in temperature from 40° F  
 $\bar{x} = x/L$   
 $\sigma$  = axial fiber stress on top glass surface

**NOTES**

- (a) Reference temperature is 40° F; no deflection was observed above that point.
- (b) Readings on gages symmetrically placed about the midpoint of the beam are averaged  $\left( \frac{s_3 + s_5}{2} \right)$ .
- (c) Failure of the beam occurred before this reading was made.
- (d) These readings are also corrected for the lateral contraction (change in thickness) of the plastic.

from the mean value at any point on the beam. The change in temperature of the beam was computed using 40° F as the initial temperature, since the plastic does not seem to have any effect on the beam above this temperature. Readings are recorded for temperature differences of 50° F to 75° F. Deflections observed on the dial gages varied from approximately -0.005 inch (negative sign indicates that the top glass surface moved downward toward the supports) over the supports to as much as +0.1122 inch at the midpoint of the beam. The deflection over the supports resulted from the contraction of the plastic in a direction perpendicular to the plane of the plate; the effect of this contraction may be separated from the flexural deflections by subtracting the deflections over the supports from the readings at other points along the beam. Since the flexural deflections would be expected to vary nearly linearly with the temperature, it is convenient to express the deflections in normalized form:

$$\bar{\delta} = \frac{(\delta/h)}{\Delta T}$$

where

$\bar{\delta}$  = normalized deflection, (in/in)/°F

$\delta$  = observed deflection corrected for the contraction of the plastic (change in thickness), in.

$h$  = total thickness of the laminate, in.

$\Delta T$  = change in temperature, °F.

If the dependence of deflection on temperature were exactly linear, the normalized deflections should be the same for each reading. Inspection of the values given in Table A-II indicates that the observed values vary

less than 5 per cent. The mean maximum deflection is 0.00563 inch per inch of beam thickness per degree temperature change.

The average flexural stress on the top surface of the glass was obtained by multiplying the elastic modulus of the glass by the flexural strains recorded from the strain indicator. A maximum flexural stress of 2260 psi was recorded at the midpoint of the beam for a temperature change of 74° F.

Since the stress is a linear function of temperature, it is again convenient to use a normalized form:

$$\bar{\sigma} = \frac{\sigma}{\Delta T}$$

where

$\bar{\sigma}$  = normalized stress, psi

$\sigma$  = observed stress, psi

$\Delta T$  = total change in temperature, °F

Inspection of the tabulated values indicates satisfactory agreement between observations of the normalized stresses at the same point on the beam for different temperatures. The mean flexural stress on the top glass surface was 26 psi/°F. Normalized deflections and stresses are plotted in Fig. A-3 and Fig. A-4.

At approximately -25° F, a fracture in the glass was observed near the end of the beam just above the plastic-glass interface. The plane of cleavage was parallel to the interface surface; in effect, a layer of glass was pulled away from the beam and adhered to the plastic. As the temperature was lowered, the crack spread along the edge toward the midpoint of the beam and simultaneously became wider. By lowering the temperature to -50° F, it was possible to separate completely a

Thickness Ratio:  $m = h_g/h_p = 1.562$

Shape Ratio:  $p = L/h = 75.90$

For theoretical curve:

$$\frac{\delta_{\max}/h}{\Delta T} = 0.005943 \text{ (in/in)/}^\circ\text{F.}$$

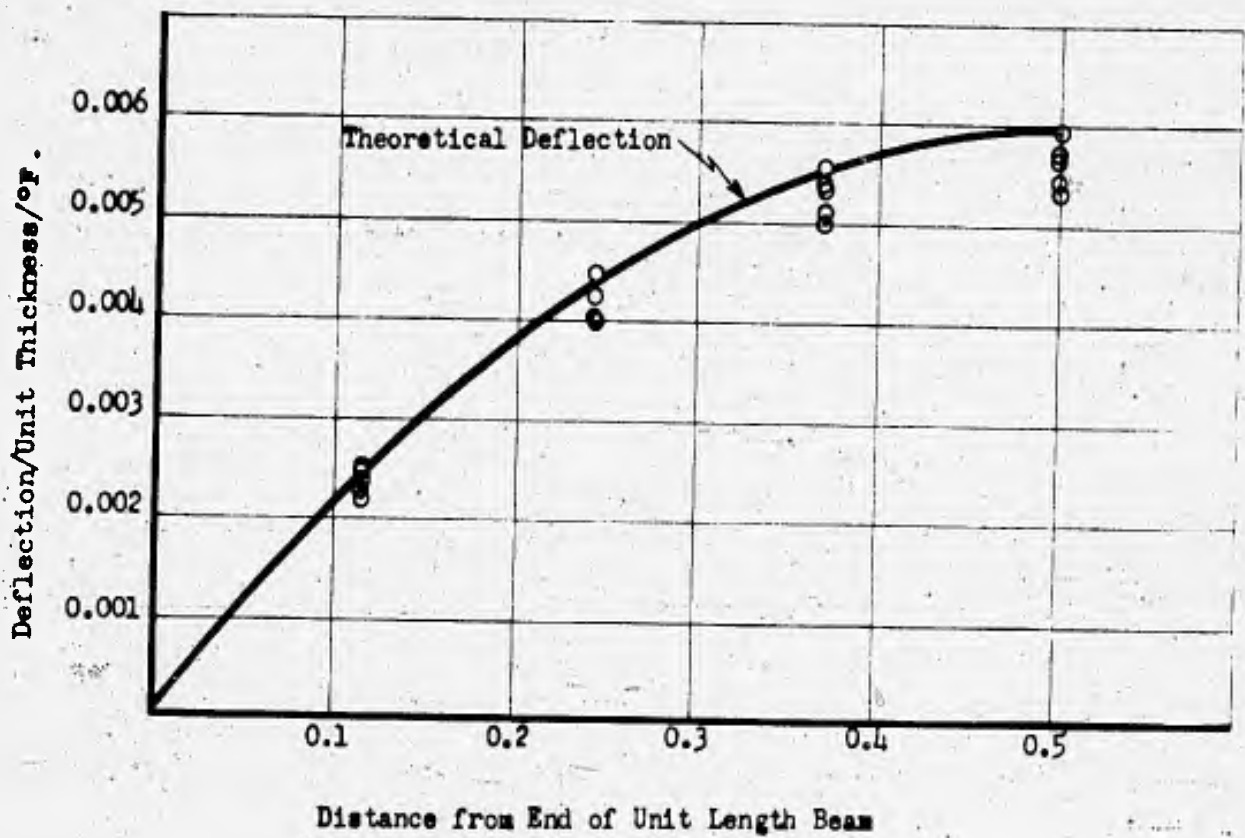


Fig. A-3 DEFLECTION CURVE OF TWO-PLY (GLASS PLASTIC) BEAM AT UNIFORM TEMPERATURE (DIAL GAGE READINGS)

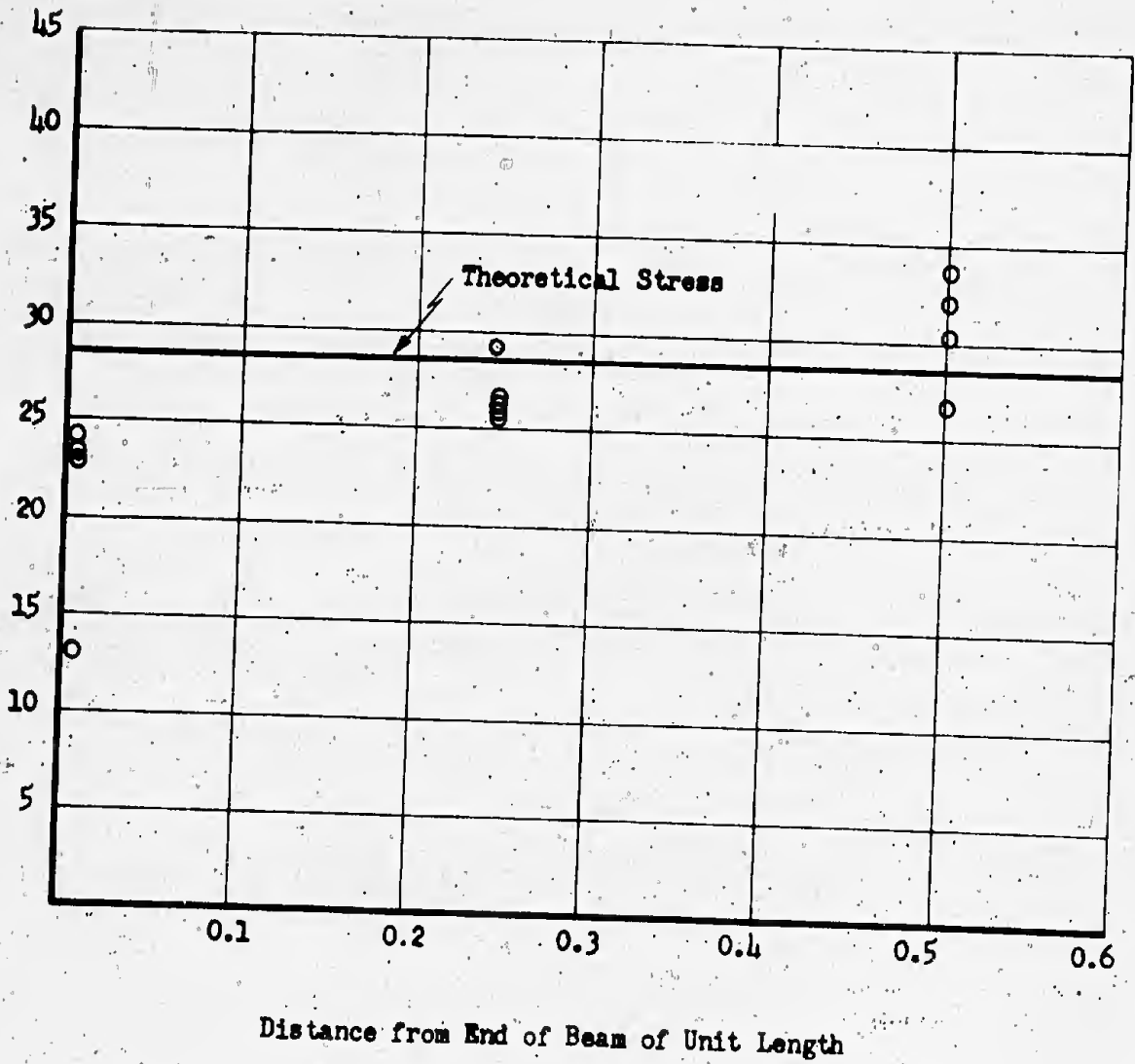
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Thickness Ratio:  $m = h_g/h_p = 1.562$   
 Shape Ratio:  $p = L/h = 75.90$

For theoretical curves:

$$\frac{\sigma}{\Delta T} = 27.26 \text{ psi/}^\circ\text{F.}$$

Fiber Stress on Top Glass Surface/Degree of Temperature Change



**Fig. A-4** MAXIMUM FIBER STRESS ON TOP SURFACE OF GLASS  
(STRAIN GAGE READINGS)

section approximately 6 inches long at the end of the beam. Fig. A-5 shows the beam after failure.

C. Experiments with Two-Fly (Glass-Plastic) Plate (Specimen No. 2)

The two-ply plate (Specimen No. 2) was pin-supported at each corner. The location of instrumentation on the specimen is shown in Fig. A-6.

The plate was placed in the insulated chamber at room temperature, and then the temperature of the chamber was gradually raised to 150° F. For temperature changes of as much as 100° which occurred above 40° F, the strains and deflections observed were negligible (less than 0.001 inch) so that the plastic may be considered to have a negligible effect on the bending of the laminate in this temperature range.

In another series of three experiments, the plate was placed in the insulated chamber at room temperature and the temperature of the chamber was gradually lowered to temperatures between 40° F and -60° F; Table A-III summarizes the experimental results. The average temperature of the plate represents the average of 10 thermocouple readings on both the top and bottom surfaces of the specimen. A dummy strain gage was mounted on a single glass pane 2 inches below the test specimen; however, no temperature measurements were recorded in this region.

It was indicated that for most measurements the temperature variation over the surface of the plate was less than  $\pm 2^\circ$  F from the mean. The change in temperature of the plate was computed using 40° F as the initial temperature since the effect of plastic is comparatively small at higher temperatures. Total temperature changes of as much as

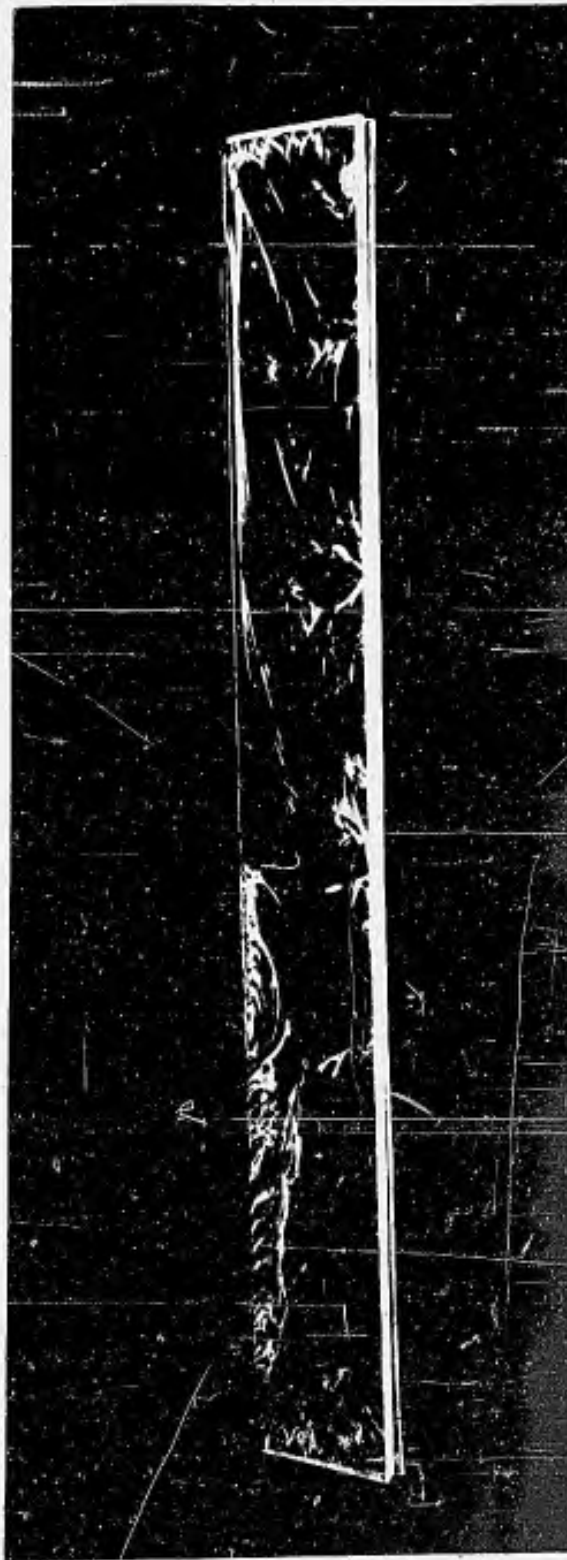


FIG. A-5 TWO-PLY (GLASS-PLASTIC) BEAM (SPECIMEN NO. 1)

AFTER FAILURE

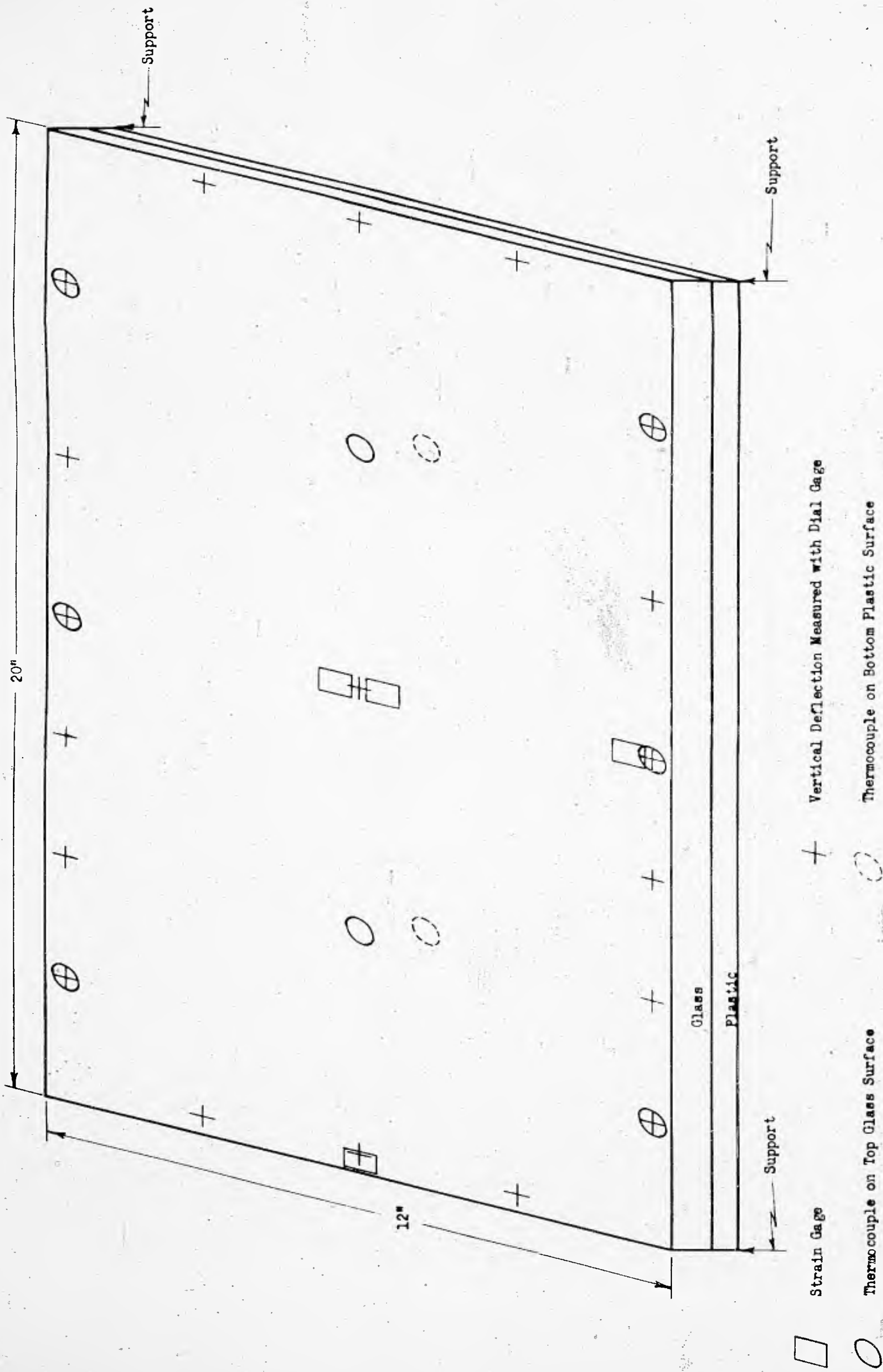
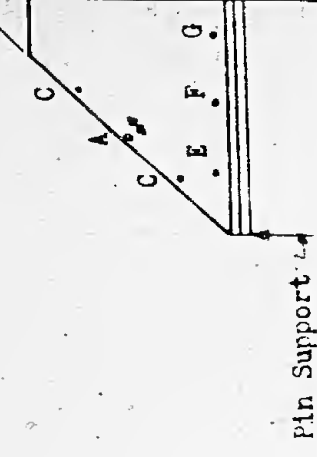


FIG. A-6 LOCATION OF MEASURING INSTRUMENTS ON TWO-PLY (GLASS-PLASTIC) PLATE (SPECIMEN No. 2)

Table A-III

STRESS AND DEFLECTION OF A TWO-PLY (GLASS-PLASTIC) LAMINATED PLATE SUBJECTED TO A UNIFORM TEMPERATURE CHANGE (SPECIMEN NO. 2)

Test Reading No.	Time from Beginning of Test, min	Average Temperature of Beam		Change (a) in Temperature, °F	Average (b) Observed Deflections (See Sketch for Location of Gages), δ, in.													
		Potentiometer Reading, mv	Temperature, °F		A	B	C	D	E	F	G	H						
I																		
1	0	+ 1.36	+ 79.3	--	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	15	+ 0.80	+ 59.8	--	0.0017	0.0040	0.0012	0.0037	0.0019	0.0018	0.0019	0.0019	0.0019	0.0019	0.0019	0.0019	0.0019	0.0019
3	30	+ 0.62	+ 53.7	--	0.0024	0.0068	0.0019	0.0063	0.0027	0.0031	0.0027	0.0027	0.0027	0.0027	0.0027	0.0027	0.0027	0.0027
4	45	+ 0.45	+ 47.6	--	0.0040	0.0120	0.0029	0.0113	0.0042	0.0058	0.0042	0.0042	0.0042	0.0042	0.0042	0.0042	0.0042	0.0042
5	60	+ 0.39	+ 45.4	--	0.0043	0.0149	0.0032	0.0131	0.0119	0.0068	0.0119	0.0119	0.0119	0.0119	0.0119	0.0119	0.0119	0.0119
6	90	+ 0.32	+ 43.1	--	0.0040	0.0122	0.0030	0.0118	0.0043	0.0062	0.0043	0.0043	0.0043	0.0043	0.0043	0.0043	0.0043	0.0043
7	120	- 0.11	+ 28.8	- 11.8	0.0109	0.0350	0.0078	0.0336	0.0120	0.0138	0.0120	0.0120	0.0120	0.0120	0.0120	0.0120	0.0120	0.0120
8	150	- 0.35	+ 20.2	- 19.8	0.0156	0.0533	0.0112	0.0503	0.0178	0.0279	0.0178	0.0178	0.0178	0.0178	0.0178	0.0178	0.0178	0.0178
9	165	- 0.33	+ 20.5	- 19.5	0.0149	0.0510	0.0108	0.0485	0.0170	0.0267	0.0170	0.0170	0.0170	0.0170	0.0170	0.0170	0.0170	0.0170
10	195	- 0.18	+ 25.7	- 14.3	0.0100	0.0350	0.0072	0.0340	0.0112	0.0180	0.0112	0.0112	0.0112	0.0112	0.0112	0.0112	0.0112	0.0112
II																		
1	0	+ 1.40	+ 82.0	--	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	15	+ 0.97	+ 67.0	--	0.0016	0.0012	0.0013	0.0022	0.0009	0.0016	0.0009	0.0009	0.0009	0.0009	0.0009	0.0009	0.0009	0.0009
3	45	+ 0.06	+ 34.0	- 6.0	0.0103	0.0337	0.0076	0.0317	0.0104	0.0180	0.0104	0.0104	0.0104	0.0104	0.0104	0.0104	0.0104	0.0104
4	60	- 0.13	+ 27.5	- 12.5	0.0117	0.0391	0.0085	0.0363	0.0123	0.0204	0.0123	0.0123	0.0123	0.0123	0.0123	0.0123	0.0123	0.0123
5	120	- 0.11	+ 28.2	- 11.8	0.0101	0.0319	0.0077	0.0304	0.0094	0.0129	0.0094	0.0094	0.0094	0.0094	0.0094	0.0094	0.0094	0.0094
6	135	- 0.14	+ 27.1	- 12.9	0.0106	0.0330	0.0079	0.0310	0.0112	0.0182	0.0112	0.0112	0.0112	0.0112	0.0112	0.0112	0.0112	0.0112
7	150	- 0.17	+ 26.1	- 13.9	0.0104	0.0371	0.0079	0.0358	0.0112	0.0215	0.0112	0.0112	0.0112	0.0112	0.0112	0.0112	0.0112	0.0112
8	165	- 0.34	+ 20.1	- 19.9	0.0148	0.0501	0.0109	0.0473	0.0116	0.0276	0.0116	0.0116	0.0116	0.0116	0.0116	0.0116	0.0116	0.0116
9	180	- 0.68	+ 10.1	- 29.9	0.0224	0.0818	0.0114	0.0765	0.0262	0.0451	0.0262	0.0262	0.0262	0.0262	0.0262	0.0262	0.0262	0.0262
10	195	- 0.85	+ 2.7	- 37.3	0.0267	0.0980	0.0196	0.0917	0.0306	0.0547	0.0306	0.0306	0.0306	0.0306	0.0306	0.0306	0.0306	0.0306
11	210	- 1.04	- 4.3	- 44.3	0.0317	0.1168	0.0232	0.1092	0.0421	0.0657	0.0421	0.0421	0.0421	0.0421	0.0421	0.0421	0.0421	0.0421
12	225	- 1.26	- 12.7	- 52.7	0.0391	0.1443	0.0286	0.1351	0.0432	0.0816	0.0432	0.0432	0.0432	0.0432	0.0432	0.0432	0.0432	0.0432
13	240	- 1.44	- 19.6	- 59.6	0.0433	0.1610	0.0319	0.1502	0.0492	0.0898	0.0492	0.0492	0.0492	0.0492	0.0492	0.0492	0.0492	0.0492
14	255	- 1.58	- 24.6	- 64.6	0.0463	0.1718	0.0340	0.1603	0.0523	0.0954	0.0523	0.0523	0.0523	0.0523	0.0523	0.0523	0.0523	0.0523
15	270	- 1.64	- 26.9	- 66.9	0.0481	0.1803	0.0354	0.1678	0.0551	0.1002	0.0551	0.0551	0.0551	0.0551	0.0551	0.0551	0.0551	0.0551
16	285	- 1.69	- 28.8	- 68.8	0.0491	0.1841	0.0361	0.1713	0.0561	0.1019	0.0561	0.0561	0.0561	0.0561	0.0561	0.0561	0.0561	0.0561
17	300	- 1.68	- 28.5	- 68.5	0.0496	0.1858	0.0364	0.1714	0.0564	0.1029	0.0564	0.0564	0.0564	0.0564	0.0564	0.0564	0.0564	0.0564
18	315	- 1.78	- 32.3	- 72.3	0.0528	0.1973	0.0394	0.1836	0.0600	0.1094	0.0600	0.0600	0.0600	0.0600	0.0600	0.0600	0.0600	0.0600
19	330	- 1.87	- 35.8	- 75.8	0.0558	0.2056	0.0405	0.1910	0.0624	0.1141	0.0624	0.0624	0.0624	0.0624	0.0624	0.0624	0.0624	0.0624
20	345	- 1.95	- 38.8	- 78.8	0.0568	0.2092	0.0412	0.1943	0.0636	0.1156	0.0636	0.0636	0.0636	0.0636	0.0636	0.0636	0.0636	0.0636
21	360	- 1.97	- 39.6	- 79.6	0.0568	0.2090	0.0413	0.1944	0.0635	0.1156	0.0635	0.0635	0.0635	0.0635	0.0635	0.0635	0.0635	0.0635
22	375	- 1.94	- 38.5	- 78.5	0.0558	0.2067	0.0410	0.1926	0.0634	0.1141	0.0634	0.0634	0.0634	0.0634	0.0634	0.0634	0.0634	0.0634
23	405	- 2.18	- 47.4	- 87.4	0.0626	0.2333	0.0460	0.2166	0.0707	0.1297	0.0707	0.0707	0.0707	0.0707	0.0707	0.0707	0.0707	0.0707
24	420	- 2.33	- 53.1	- 93.1	0.0663	0.2469	0.0489	0.2298	0.0748	0.1373	0.0748	0.0748	0.0748	0.0748	0.0748	0.0748	0.0748	0.0748
III																		
1	0	+ 1.39	+ 80.3	--	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	60	- 1.95	- 38.8	- 78.8	0.0585	0.2196	0.0436	0.2057	0.0626	0.1198	0.0626	0.0626	0.0626	0.0626	0.0626	0.0626	0.0626	0.0626
3	75	- 2.24	- 49.6	- 89.6	0.0633	0.2323	0.0470	0.2221	0.0718	0.1267	0.0718	0.0718	0.0718	0.0718	0.0718	0.0718	0.0718	0.0718
4(c)	90	- 2.35	- 53.8	- 93.8	0.0664	0.2432	0.0486	0.2275	0.0733	0.1295	0.0733	0.0733	0.0733	0.0733	0.0733	0.0733	0.0733	0.0733
5(c)	105	- 2.40	- 56.0	- 96.0	0.0670	0.2452	0.0490	0.2298	0.0740	0.1306	0.0740	0.0740	0.0740	0.0740	0.0740	0.0740	0.0740	0.0740
6(c)	120	- 2.43	- 56.9	- 96.9	0.0557	0.2120	0.0408	0.1990	0.0661	0.1172	0.0661	0.0661	0.0661	0.0661	0.0661	0.0661	0.0661	0.0661



Nomenclature

- $h_g$  = thickness of glass layer
- $h_p$  = thickness of plastic layer
- $h = h_g + h_p$  = total thickness of plate
- $L$  = maximum span of plate (diagonal)
- $m = h_g/h_p$  = thickness ratio
- $p = L/h$  = shape ratio
- $\Delta T$  = change in temperature (from 70°F)
- $\delta$  = deflection of plate
- $\sigma_x, \sigma_y$  = fiber stresses on top glass

(a) A reference temperature of 40°F plastic occurs at this temperature. The paratively small.

(b) Readings from dial gages in symme

(c) These data were obtained after fa

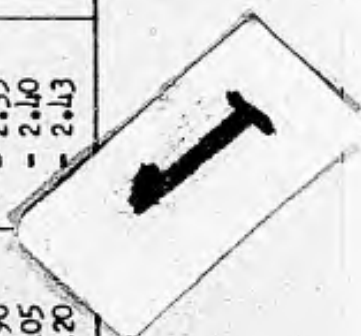


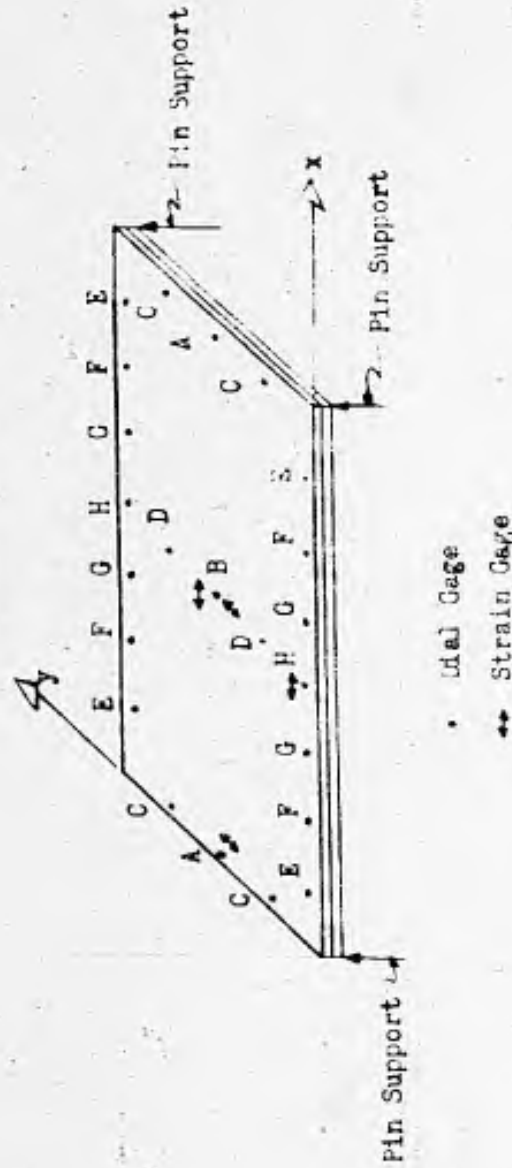
Table A-III

LAMINATED PLATE SUBJECTED TO A UNIFORM TEMPERATURE CHANGE (SPECIMEN NO. 2)

Average (b) Observed Deflections (See Sketch for Location of Gages),  $\delta$ .

	A	B	C	D	E	F	G	H
in.	in.	in.	in.	in.	in.	in.	in.	in.
0	0.0017	0	0.0012	0	0	0	0	0
1	0.0024	0.0040	0.0019	0.0037	0.0019	0.0018	0.0027	0.0030
2	0.0040	0.0068	0.0019	0.0063	0.0027	0.0031	0.0043	0.0050
3	0.0043	0.0120	0.0029	0.0113	0.0042	0.0058	0.0080	0.0088
4	0.0040	0.0149	0.0032	0.0131	0.0119	0.0068	0.0091	0.0100
5	0.0040	0.0122	0.0030	0.0118	0.0043	0.0062	0.0082	0.0090
6	0.0109	0.0350	0.0078	0.0336	0.0120	0.0188	0.0248	0.0270
7	0.0156	0.0533	0.0112	0.0503	0.0178	0.0279	0.0373	0.0408
8	0.0149	0.0510	0.0108	0.0485	0.0170	0.0267	0.0353	0.0388
9	0.0100	0.0350	0.0072	0.0340	0.0112	0.0180	0.0239	0.0262
10	0	0	0	0	0	0	0	0
11	0.0016	0.0032	0.0013	0.0022	0.0009	0.0016	0.0030	0.0022
12	0.0103	0.0337	0.0076	0.0317	0.0104	0.0180	0.0232	0.0253
13	0.0117	0.0391	0.0085	0.0363	0.0121	0.0204	0.0264	0.0290
14	0.0101	0.0319	0.0077	0.0304	0.0096	0.0125	0.0214	0.0245
15	0.0106	0.0330	0.0079	0.0310	0.0112	0.0182	0.0254	0.0254
16	0.0104	0.0371	0.0079	0.0358	0.0132	0.0235	0.0264	0.0284
17	0.0148	0.0501	0.0109	0.0473	0.0166	0.0276	0.0355	0.0385
18	0.0224	0.0818	0.0114	0.0765	0.0262	0.0451	0.0588	0.0634
19	0.0267	0.0980	0.0196	0.0917	0.0306	0.0517	0.0696	0.0744
20	0.0317	0.1168	0.0232	0.1092	0.0421	0.0657	0.0817	0.0877
21	0.0391	0.1443	0.0286	0.1351	0.0432	0.0816	0.1002	0.1075
22	0.0433	0.1610	0.0319	0.1502	0.0492	0.0898	0.1111	0.1191
23	0.0463	0.1718	0.0340	0.1603	0.0523	0.0954	0.1184	0.1270
24	0.0481	0.1803	0.0354	0.1678	0.0551	0.1002	0.1241	0.1331
25	0.0491	0.1841	0.0361	0.1713	0.0561	0.1019	0.1265	0.1360
26	0.0496	0.1858	0.0364	0.1714	0.0564	0.1029	0.1276	0.1372
27	0.0528	0.1973	0.0394	0.1836	0.0600	0.1096	0.1315	0.1452
28	0.0558	0.2056	0.0405	0.1910	0.0624	0.1141	0.1444	0.1522
29	0.0568	0.2092	0.0412	0.1943	0.0636	0.1156	0.1435	0.1542
30	0.0568	0.2090	0.0413	0.1944	0.0635	0.1156	0.1434	0.1542
31	0.0558	0.2067	0.0410	0.1926	0.0634	0.1141	0.1439	0.1532
32	0.0626	0.2333	0.0460	0.2166	0.0707	0.1297	0.1602	0.1721
33	0.0663	0.2469	0.0489	0.2298	0.0748	0.1373	0.1696	0.1821
34	0	0	0	0	0	0	0	0
35	0.0585	0.2196	0.0436	0.2057	0.0626	0.1198	0.1515	0.1629
36	0.0633	0.2323	0.0470	0.2221	0.0718	0.1267	0.1597	0.1718
37	0.0664	0.2432	0.0486	0.2275	0.0733	0.1295	0.1627	0.1702
38	0.0670	0.2452	0.0490	0.2298	0.0740	0.1306	0.1641	0.1762
39	0.0557	0.2120	0.0408	0.1990	0.0661	0.1172	0.1656	0.1575

Location of Gages



Nomenclature

$h_g$  = thickness of glass layer

$h_p$  = thickness of plastic layer

$h = h_g + h_p$  = total thickness of plate

$L$  = maximum span of plate (diagonal)

$m = h_g/h_p$  = thickness ratio

$p = L/h$  = shape ratio

$\Delta T$  = change in temperature (from 40° F)

$\delta$  = deflection of plate

$\sigma_x, \sigma_y$  = fiber stresses on top glass surface

Dimensions

$h_g = 0.1875$  in.

$h_p = 0.1200$  in.

$h = 0.3075$  in.

$L = 23.35$  in.

$m = 1.562$

$p = 75.84$

Notes

(a) A reference temperature of 40° F was used because a marked change in the physical properties of the plastic occurs at this temperature. The deflections of the laminated plate which occur above 40° F are comparatively small.

(b) Readings from dial gages in symmetrical positions are averaged.

(c) These data were obtained after failure.

2





97° F were obtained. A maximum deflection of 1/4 inch was obtained at the center of the plate. No deflection measurements were made over the supports so that the effect of the contraction of the plastic perpendicular to the plane of the plate could not be determined in this series of experiments.

The flexural deflections should vary nearly linearly with temperature; therefore, it is convenient again to express the deflections in normalized form:

$$\bar{\delta} = \frac{(\delta/h)}{\Delta T}$$

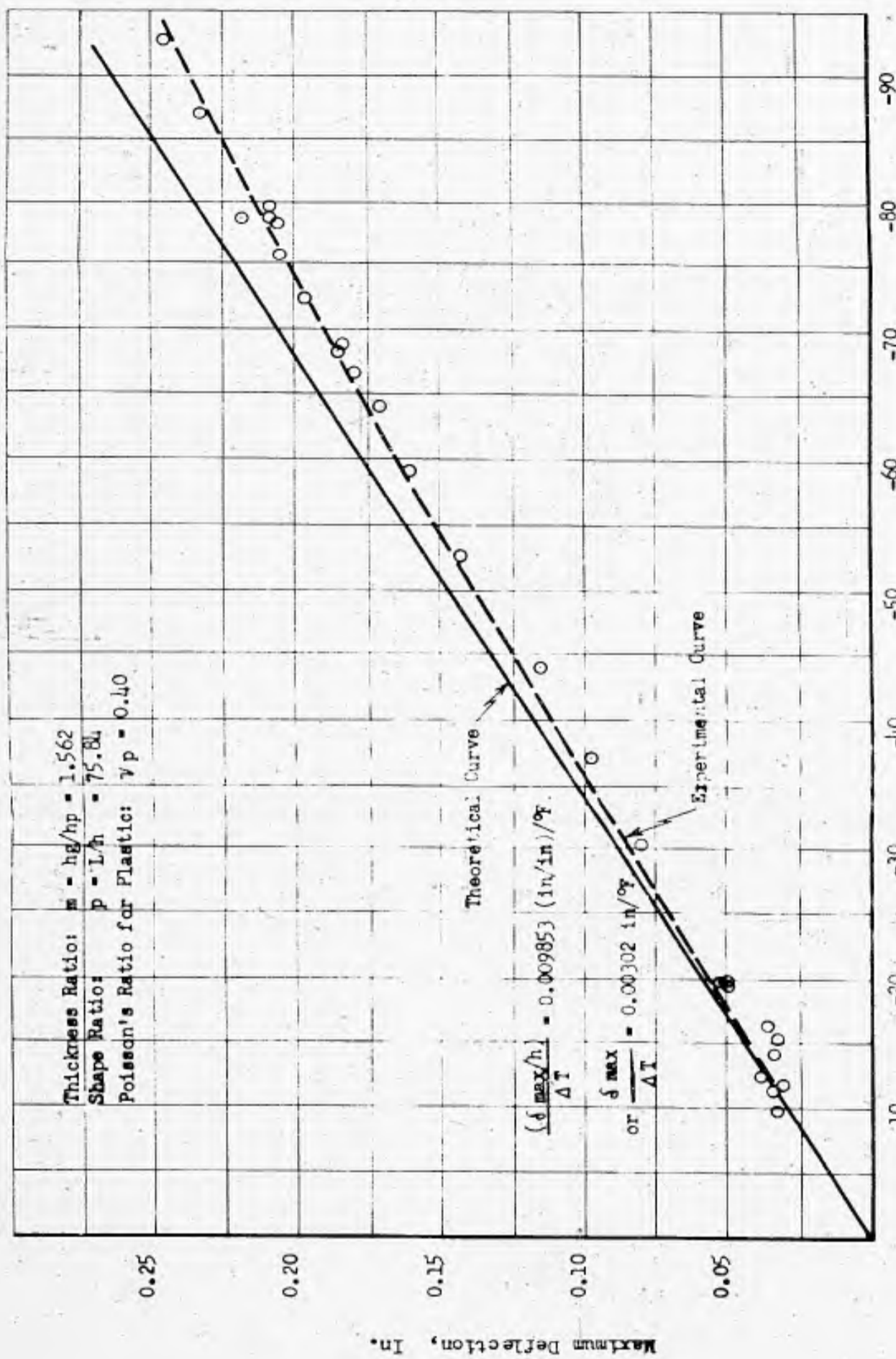
Maximum deflections at the center of the plate as a function of temperature are plotted in Fig. A-7. Normalized deflections as a function of position on the plate are plotted in Fig. A-8. Inspection of the values given in Table A-III indicates that the observed deflections expressed in normalized form vary less than 10 per cent from the mean value of 0.00879 (in/in)/°F.

In the center of the plate, two strain gages were placed so as to measure the strain in perpendicular directions. The stress in these directions may then be obtained from the stress-strain relations,

$$\sigma_x = \frac{E}{1 - \nu^2} (\epsilon_x + \nu \epsilon_y)$$

and

$$\sigma_y = \frac{E}{1 - \nu^2} (\nu \epsilon_x + \epsilon_y)$$



Change in temperature,  $^\circ\text{F.}$  (Reference Temperature Is  $40^\circ\text{F.}$ )

FIG. A-7 MAXIMUM DEFLECTION OF PLATE (SPECIMEN No. 2) AS A FUNCTION OF TEMPERATURE CHANGE BELOW  $40^\circ\text{F.}$

The letters A,B, . . . ,H represent dial gages

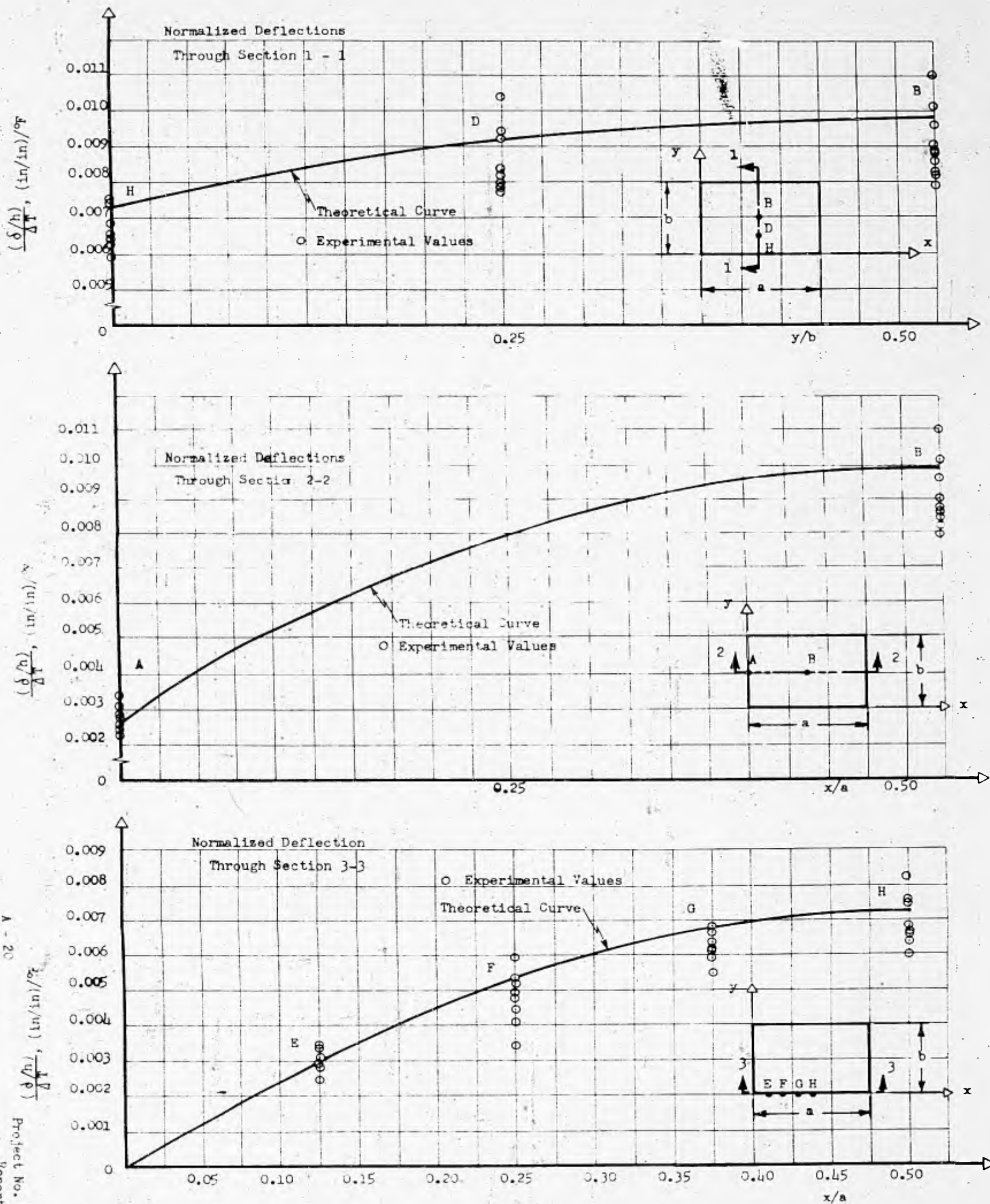


Fig. A-8 NORMALIZED DEFLECTION OF TWO-PLY (GLASS-PLASTIC) PLATE SUBJECTED TO A UNIFORM TEMPERATURE CHANGE

where

$\sigma_x, \sigma_y$  = normal stresses

$E_g$  = modulus of elasticity of the glass

$\nu_g$  = Poisson's ratio for the glass

$e_x, e_y$  = normal strains in the direction of the length and width of the plate, respectively.

A maximum flexural stress of 4839 psi was observed at the center of the plate for a temperature change of 93°F.

Single strain gages were also placed along the edges of the plate at two places (Positions A and H on the diagram in Table A-III); however, these gages measured the strain in one direction only and, therefore, stresses obtained from these readings by multiplying by the elastic modulus for glass necessarily neglect the effect of Poisson's ratio. Nevertheless, stress values computed in this manner are also included in Table A-III. The maximum stress at the center of the plate is plotted as function of the change in temperature in Fig. A-9.

At approximately -50°F, a fracture in the glass similar to that which occurred in the beam was observed near a corner of the plate just above the interface. As the temperature of the plate was lowered to -60°F, the failure spread along the edge of the plate and simultaneously became wider.

### III. DISCUSSION OF GLASS FAILURES IN COLD TESTS

In the low temperature test of the beam (Specimen No. 1), failure occurred at a temperature of -25° F. The failure consisted of a single crack in the glass near one corner of the beam, just above and parallel to the glass-plastic interface (Fig A-10). By lowering the temperature of the specimen it was possible to cause the crack to propagate into the interior of the beam. At approximately -40° F, another crack appeared

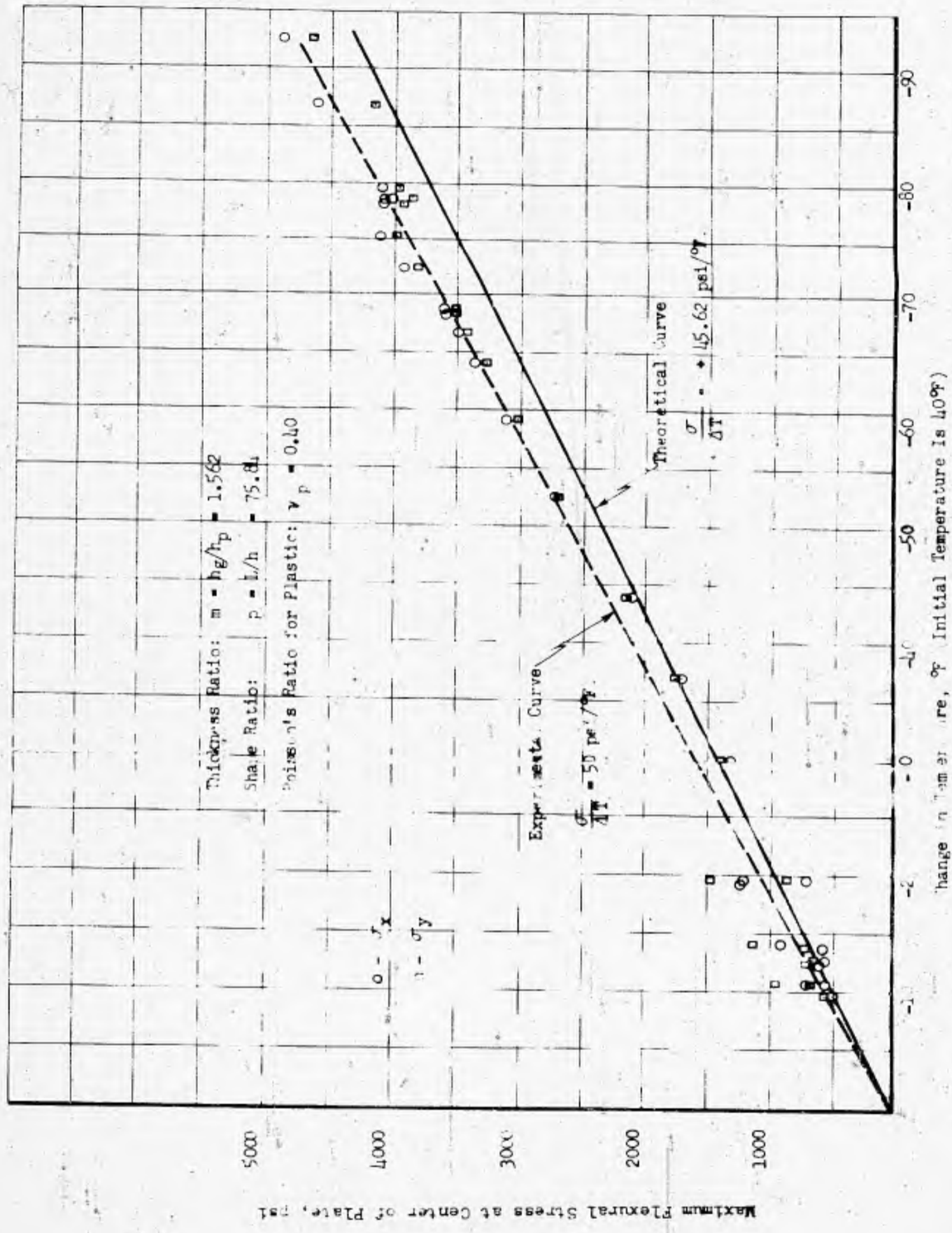


FIG. A-9 MAXIMUM FLEXURAL STRESS ON TOP PLATE SURFACE AT CENTER OF PLATE (SPECIMEN No. 2) AS A FUNCTION OF TEMPERATURE CHANGE BELOW 40°F.

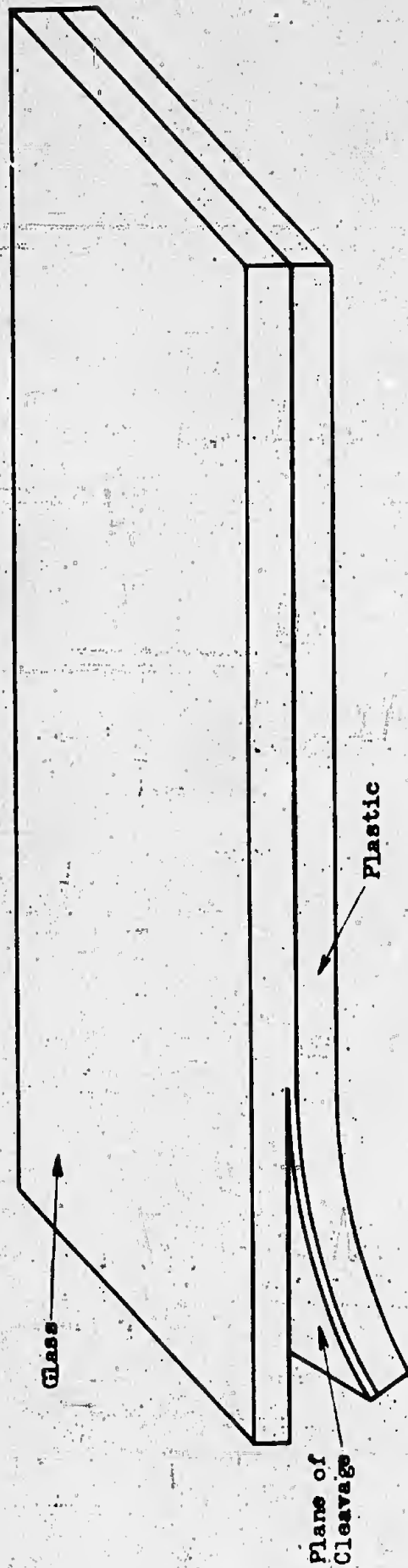


FIG. A-10 SKETCH OF BEAM (SPECIMEN No. 2) SHOWING PLANE OF CLEAVAGE

Project No. 90-692j  
Report No. 36

at another corner of the beam and also propagated into the interior. At -50° F, the two cracks covered 80 per cent of the area of the beam (Fig. A-11).

The glass which adhered to the plastic separated from the failure surface in one piece without breaking. The thickness of this layer varied from 0.010 to 0.025 inch.

The fracture surface exhibited a system of tiny scratches. These scratches were examined by a photographic technique suggested by C. D. Oughton.\* According to this method a photogram of the fracture surface is taken by placing a piece of sensitized photographic paper directly under the glass and projecting light through the fracture surface (Fig. A-12). A standard photographic enlarger was used as the light source. It was found that the smallest possible diaphragm aperture (f29) was necessary to get good definition of the lines on the fracture surface.

A photogram taken in this fashion is shown in Fig. A-13. J. B. Murgatroyd\*\* first originated a nomenclature for glass markings of this type. The long arcs (Fig. A-13) are called "rib" lines and represent rest points in the forward movement of the fracture. Thus, the rib lines indicate crack propagation fronts and show the direction in which the failures travel. The fine lines perpendicular to rib lines are called "hackle" marks. They occur when glass fails under a strong shearing force and probably represent minute cracks in the glass as it peels away from the fracture surface.

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\*C. D. Oughton, "Analysis of Glass Fractures", Glass Industry, February, 1945, p. 72.

\*\*J. B. Murgatroyd, "The Significance of Surface Marks on Fractured Glass", Journal of the Society for Glass Technology, XXVI (1942), 156.

Top View of Beam (Specimen No. 1)

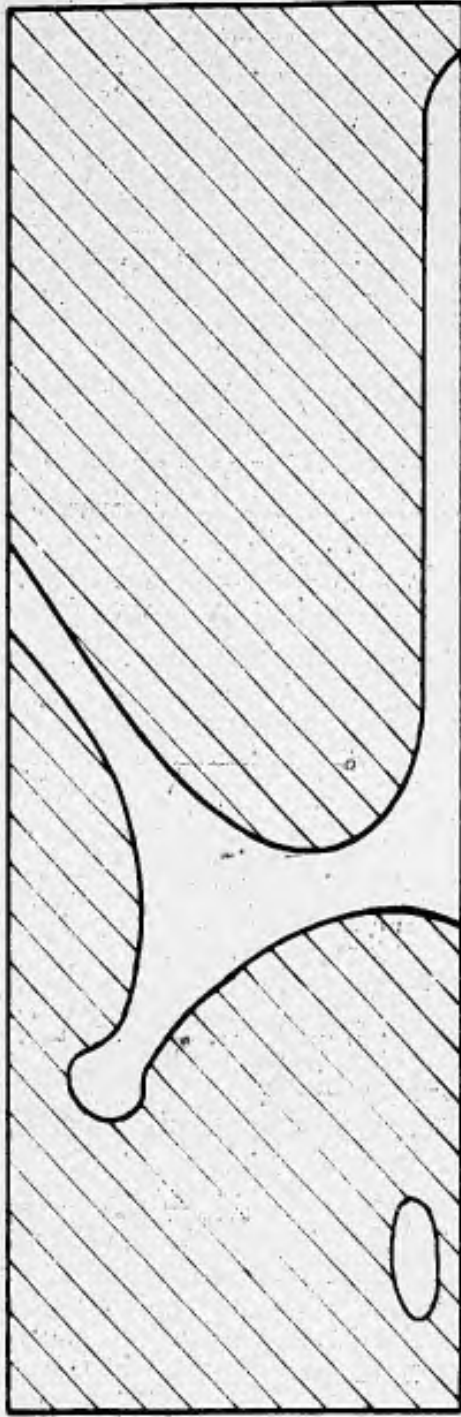
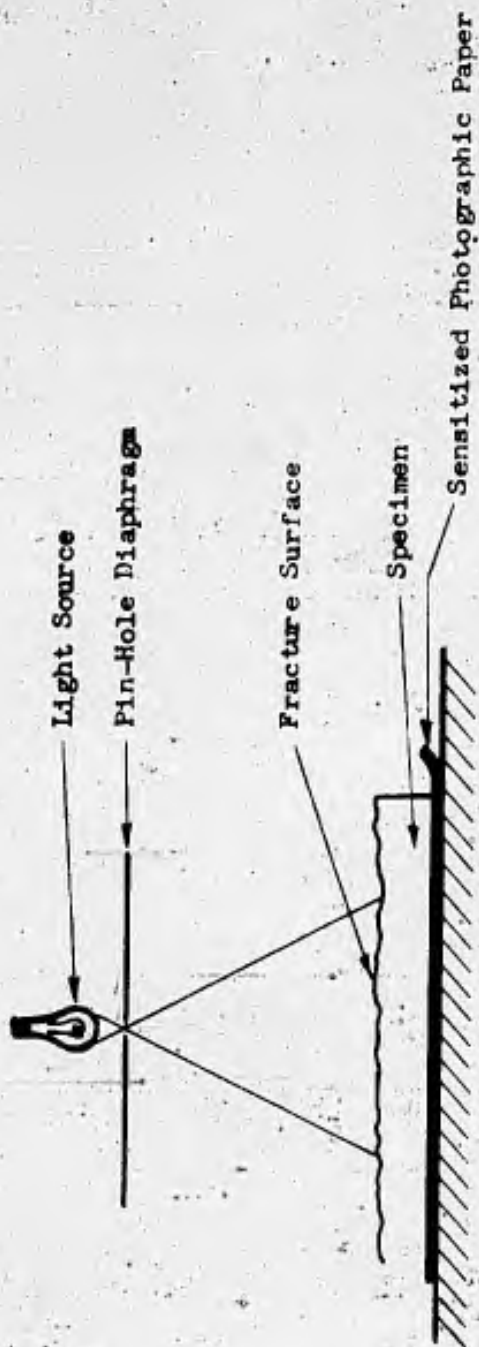
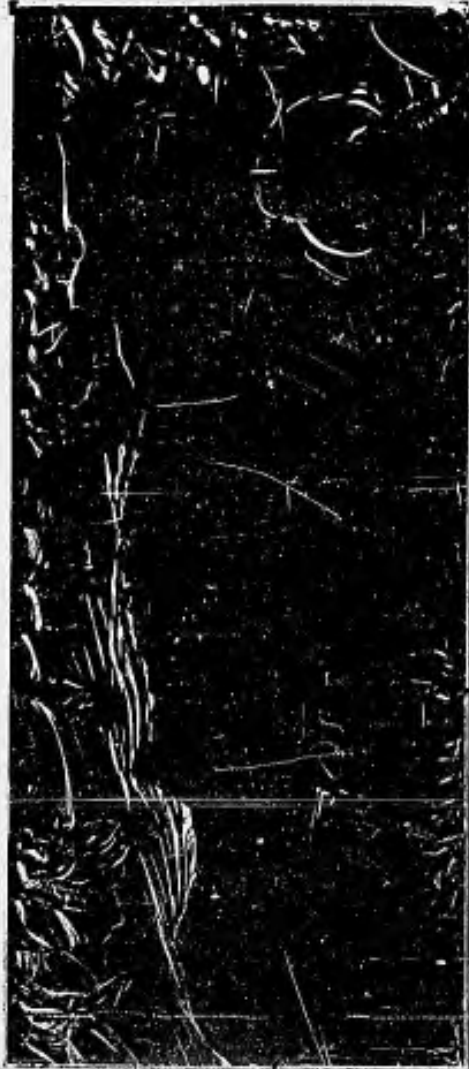


FIG. A-11 SHADED AREA SHOWS EXTENT OF CRACK AT  $-50^{\circ}$  F IN BEAM



**FIG. A-12 TECHNIQUE FOR OBTAINING PHOTOGRAMS OF FRACTURE SURFACE**

Polished Edge



Hackle  
Marks

Polished  
End

Rib Lines

Sawed Edge

FIG. A-13 PHOTOMICROGRAM OF FRACTURE SURFACE: TRO-PLY GLASS-PLASTIC LAMINATE

SUBJECT TO UNIFORM TEMPERATURE CHANGE (ACTUAL SIZE)

The specimen used in the experiment was sawed from a larger laminated plate and the sawed edge was not polished. Inspection of Fig. A-13 indicates that failures began at tiny cracks along the sawed edge, joining with other failures as they grew larger, and finally moved toward the centerline of the beam as one crack. The other edge of the beam was factory-polished and the failure at this edge appears to have started independently at points approximately 1/8 inch from the edge. Between the edge and beginning of the glass failures the glass and plastic appear to have delaminated. The failure at the polished edge began at lower temperatures than the failure at the sawed edge.

#### IV. THEORETICAL DETERMINATION OF DEFLECTIONS AND FLEXURAL STRESSES

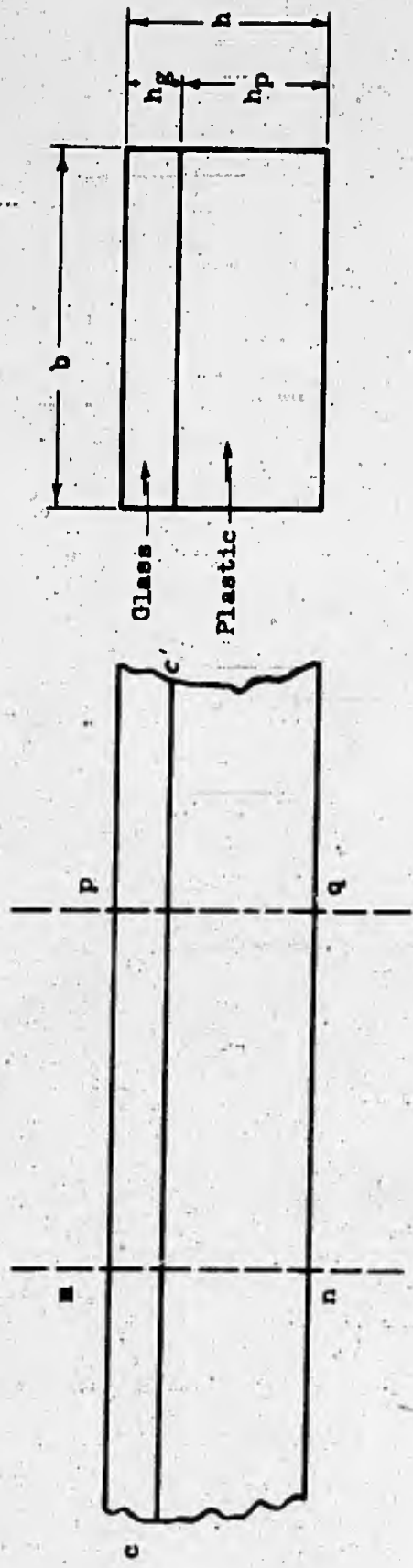
The deflections and flexural stresses in a two-ply beam subjected to a uniform change in temperature may be obtained by using the theory developed by S. Timoshenko.\* The theory is recapitulated below and extended to two-ply plates.

##### A. Theory for Two-Ply Beams

Consider a slender beam made up of a plastic strip laminated to the bottom of a glass pane (Fig. A-14). Because the thermal coefficient of the plastic is greater than that of the glass, an increase in temperature will cause bending of the beam with the concave side upward. Assume that the bending moment and the axial normal force in each layer does not vary along the length of the beam. Consider an element of the beam cut out by two adjacent sections, mn and pq. The resultant of the stresses

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\*Op. cit. See also S. Timoshenko, Strength of Materials, Part 1, Second Edition, D. Van Nostrand (New York), 1940, pp. 218-219.



**Fig. A-114 TWO-PLY BEAM**

acting on the cut section of each layer will be statically equivalent to a normal force and a couple. (The shear force is neglected.)

The following notations will be used in the theoretical analysis:

$b$  = width of beam

$E_g$  = elastic modulus of glass

$E_p$  = elastic modulus of plastic

$h_g$  = thickness of glass layer

$h_p$  = thickness of plastic layer

$h = h_g + h_p$  = total thickness of beam

$I_g$  = moment of inertia of glass cross section about  
centroidal axis

$I_p$  = moment of inertia of plastic cross section about  
centroidal axis

$L$  = length of finite beam

$m = h_g/h_p$  = thickness ratio

$n = E_g/E_p$  = ratio of elastic moduli

$p = L/h$  = shape ratio

$r$  = radius of curvature of beam

$F_1, M_1$  = force and couple statically equivalent to normal stresses acting on cross section of glass layer

$F_2, M_2$  = force and couple statically equivalent to normal stresses acting on cross section of plastic layer

$\Delta T$  = increase in temperature of beam from unstressed condition

$\alpha_g$  = thermal coefficient of expansion of glass

$\alpha_p$  = thermal coefficient of expansion of plastic

$\delta$  = deflection of beam

$\delta_{max}$  = maximum deflection of beam

$s$  = distance from midpoint of beam

$\sigma$  = fiber stress on top glass surface

Since there are no external forces acting on the beam, the resultant force and couple on any section must be zero. Therefore,

$$F_1 = F_2 = F \quad (A-1)$$

and

$$\frac{F(h_g + h_p)}{2} = M_1 + M_2 \quad (A-2)$$

But from the usual beam theory:

$$M_1 = \frac{E I}{r} \quad \text{and} \quad M_2 = \frac{E I}{r} \quad (A-3)$$

so that Eq. (A-2) becomes:

$$\frac{h}{2} F - (E_g I_g + E_p I_p) \frac{1}{r} = 0 \quad (A-4)$$

The axial strain on the interface surface must be the same in both the glass and plastic layers, so that

$$\alpha_g \Delta T + \frac{F_1}{E_g h_g b} + \frac{h_g}{2r} = \alpha_p \Delta T - \frac{F_2}{E_p h_p b} - \frac{h_p}{2r}$$

or

$$\left( \frac{1}{E_g h_g b} + \frac{1}{E_p h_p b} \right) F + \frac{h}{2r} = (\alpha_p - \alpha_g) \Delta T \quad (A-5)$$

Solving Eqs. (A-4) and (A-5) simultaneously for  $1/r$  gives

$$\frac{1}{r} = \frac{h (\alpha_p - \alpha_g) \Delta T}{2 \left[ \frac{h^2}{E} + (E_g I_g + E_p I_p) \left( \frac{1}{E_g h_g b} + \frac{1}{E_p h_p b} \right) \right]} \quad (A-6)$$

\* S. Timoshenko, Strength of Materials, Part 1, 2nd edition, D. Van Nostrand Co. (New York, 1940), p. 91.

Equation (A-6) can be written in terms of the ratios of the thicknesses and elastic moduli of the two layers; thus, make the substitutions:

$$m = \frac{h_g}{h_p} \quad \text{and} \quad n = \frac{E_g}{E_p} \quad (\text{A-7})$$

and use the expressions for moment of inertia:

$$I_g = \frac{bh_g^3}{12} \quad \text{and} \quad I_p = \frac{bh_p^3}{12}$$

Then:

$$\frac{h}{r \Delta T} = \frac{6(1+m)^2(\alpha_p - \alpha_g)}{3(1+m)^2 + (1+m^3n)(1 + \frac{1}{mn})} \quad (\text{A-8})$$

The maximum deflection of a simply supported beam of length  $L$  will be given by the altitude of a segment bounded by a circular arc of length  $L$  and its subtended chord:

$$\delta_{\max} = \frac{L^2}{8r}$$

or

$$\frac{(\delta_{\max}/h)}{\Delta T} = \frac{p^2}{8} \left( \frac{h}{r \Delta T} \right) \quad (\text{A-9})$$

where  $p = L/h$ .

If the origin of coordinates is taken at the center of the span, the deflection curve is given approximately by:

$$\delta = \delta_{\max} \left[ 1 - 4(\xi/L)^2 \right] \quad (\text{A-10})$$

The fiber stress at the top glass surface is the algebraic sum of the flexural stress and normal stress:

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$$\sigma = \frac{F}{bh} - \frac{h E}{2r}$$

or

$$\frac{\sigma}{\Delta T} = - E_g \left( \frac{h}{r \Delta T} \right) \left[ \frac{2m^2 + 3m - \frac{1}{mn}}{6(1+m)^2} \right] \quad (A-11)$$

The negative sign indicates that a temperature increase gives rise to compressive stresses.

Deflections and stresses are computed in Table A-IV for a beam having dimensions identical to those of the beam used in the experimental work. The predicted deflections and stresses are also compared with the observed values in Figs. A-3 and A-4.

#### B. Theory for Two-Ply Plates

Consider a plate of infinite extent made up of a plastic layer laminated to the bottom of a glass pane. If the temperature of the laminate is changed, the plate will bend due to the difference in the thermal coefficients of expansion of the glass and plastic. Assume that the normal stresses do not vary over the area of the plate (they may possibly vary over the thickness) and are independent of direction. Consider a cylindrical element cut from the plate as shown in Fig. A-15. The stresses on the cut section will be uniformly distributed around the circumference; further, the stresses on each layer will be statically equivalent to a load and a couple uniformly distributed around the cross section.

The following nomenclature will be used in the theoretical analysis of this bending.

a = length of finite plate

**Table A-IV**  
**THEORETICAL DEFLECTIONS AND STRESSES IN A TWO-PLY (GLASS-PLASTIC) LAMINATED BEAM SUBJECTED TO A UNIFORM CHANGE IN TEMPERATURE**

$L = 20 \text{ in.}$   
 $b = 3 \text{ in.}$   
 $p = L/h = 20/0.3075 = 65.04$   
 $\alpha_g = 4.6 \times 10^{-6} \text{ in/in/}^\circ\text{F}$   
 $E_g = 10 \times 10^6 \text{ psi}$   
 $h_g = 0.1875 \text{ in.}$   
 $\alpha_p = 63 \times 10^{-6} \text{ in/in/}^\circ\text{F}$   
 $E_p = 0.21 \times 10^6 \text{ psi}$   
 $h_p = 0.1200 \text{ in.}$   
 $h = h_g + h_p = 0.3075 \text{ in.}$   
 $m = h_g/h_p = 1.562$   
 $n = E_g/E_p = 47.62$

Formula	Calculation	Result
$\frac{h}{r\Delta T} = \frac{6(1+m)^2(\alpha_p - \alpha_g)}{3(1+m)^2 + (1+m^3n)(1 + \frac{1}{mn})}$	$\frac{6[1 + (1.562)]^2 [(63)(10^{-6}) - (4.6)(10^{-6})]}{(3)[1 + (1.562)]^2 + [1 + (1.562)^3(47.62)] \left[ 1 + \frac{1}{(1.562)(47.62)} \right]}$	$11.24 \times 10^{-6} \text{ (in/in)/}^\circ\text{F}$
$\frac{(6 \frac{\max}{\Delta T} / h) - E_p \left( \frac{h}{r\Delta T} \right)^2}{8} \left( \frac{h}{r\Delta T} \right)$	$\frac{(65.04)^2 (11.24)(10^{-6})}{8}$	$0.005943 \text{ (in/in)/}^\circ\text{F}$
$\frac{\sigma}{\Delta T} = -E_g \left( \frac{h}{r\Delta T} \right) \left[ \frac{2m^2 + 3m - \frac{1}{mn}}{6(1+m)^2} \right]$	$-(10)(10^6)(11.24)(10^{-6}) \left\{ \frac{(2)(1.562)^2 + (3)(1.562) - \frac{1}{(1.562)(47.62)}}{(6)[1 + (1.562)]^2} \right\}$	$- 27.26 \text{ psi/}^\circ\text{F}$ (Minus sign indicates compression for temperature increase.)

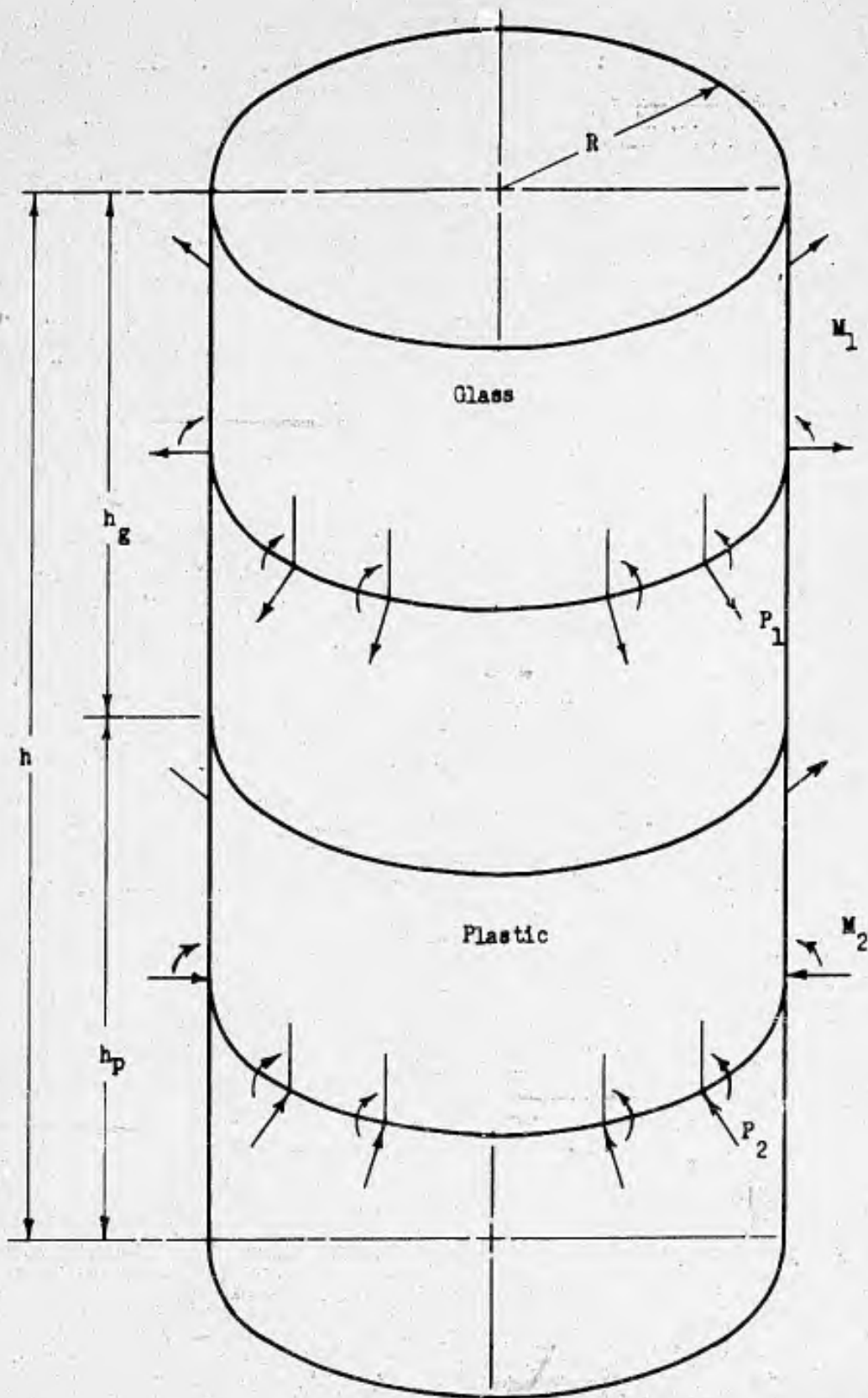


FIG. A-15 CYLINDRICAL ELEMENT OF TWO-PLY PLATE

$b$  = width of finite plate

$D_g$  = flexural rigidity of glass pane

$D_p$  = flexural rigidity of plastic layer

$E_g$  = elastic modulus of glass

$E_p$  = elastic modulus of plastic

$h_g$  = thickness of glass pane

$h_p$  = thickness of plastic layer

$h = h_g + h_p$  = total thickness of beam

$L = \sqrt{a^2 + b^2}$  = maximum distance between supports

$m = h_g/h_p$  = thickness ratio

$n = E_g/E_p$  = ratio of elastic moduli

$p = L/h$  = shape ratio

$q = \left( \frac{1 - \nu_g}{1 - \nu_p} \right) =$  constant dependent on Poisson's ratio

$r$  = radius of curvature of plate

$F_1, M_1$  = force and couple per unit length statically equivalent to normal stresses on lateral surface of glass pane

$F_2, M_2$  = force and couple per unit length statically equivalent to normal stresses on lateral surfaces of plastic

$\Delta T$  = increase in temperature of beam from unstressed condition

$\alpha_g$  = thermal coefficient of expansion of glass

$\alpha_p$  = thermal coefficient of expansion of plastic

$\delta$  = deflection of plate perpendicular to its plane

$\delta_{max}$  = maximum deflection of plate

$\nu_g$  = Poisson's ratio for glass

$\nu_p$  = Poisson's ratio for plastic

$\xi$  = distance from midpoint of plate

$\sigma_x$  = fiber stress on top glass surface parallel to length of plate

$\sigma_y$  = fiber stress on top glass surface parallel to width of plate.

Because there are no external forces acting on the plate, the resultant force and couple on any internal surface must be zero.

Therefore:

$$F_1 = F_2 = P \quad (A-12)$$

and

$$\frac{F(h_g + h_p)}{2} = M_1 + M_2 \quad (A-13)$$

But from the usual plate theory:\*

$$M_1 = \frac{(1 + \nu_g) D_g}{r} \quad \text{and} \quad M_2 = \frac{(1 + \nu_p) D_p}{r} \quad (A-14)$$

so that Eq. (A-13) becomes:

$$\frac{h}{2} P - \left[ (1 + \nu_g) D_g + (1 + \nu_p) D_p \right] \frac{1}{r} = 0 \quad (A-15)$$

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\*S. Timoshenko, Theory of Plates and Shells, McGraw Hill Book Co., (New York, 1940), pp. 34-52.

The radial strain on the interface must be the same in both the glass and plastic layers, so that:

$$\alpha_g \Delta T + (1 - \nu_g) \frac{P_1}{h_g E_g} + (1 - \nu_g) \frac{h_g}{2r} = \alpha_p \Delta T - (1 - \nu_p) \frac{P_2}{h_p E_p} - (1 - \nu_p) \frac{h_p}{2r}$$

or

$$\left( \frac{1 - \nu_g}{h_g E_g} + \frac{1 - \nu_p}{h_p E_p} \right) \frac{h_g + h_p}{2} + \frac{(1 - \nu_g) h_g + (1 - \nu_p) h_p}{2} \left( \frac{1}{r} \right) = (\alpha_p - \alpha_g) \Delta T \quad (A-16)$$

Solving Eqs. (A-15) and (A-16) simultaneously gives:

$$\frac{1}{r} = \frac{h(\alpha_p - \alpha_g) \Delta T}{2 \left\{ \frac{h \left[ \frac{(1 - \nu_g) h_g + (1 - \nu_p) h_p}{4} + \left[ (1 + \nu_g) D_g + (1 + \nu_p) D_p \right] \right] \left[ \frac{1 - \nu_g}{h_g E_g} + \frac{1 - \nu_p}{h_p E_p} \right]} \right\}} \quad (A-17)$$

Using the definition of flexural rigidity:

$$D_g = \frac{E_g h_g^3}{12(1 - \nu_g^2)} \quad \text{and} \quad D_p = \frac{E_p h_p^3}{12(1 - \nu_p^2)}$$

and making the substitutions:

$$m = \frac{h_g}{h_p}, \quad n = \frac{E_g}{E_p}, \quad \text{and} \quad q = \frac{1 - \nu_g}{1 - \nu_p}$$

Eq. (A-17) becomes:

$$\frac{h}{r \Delta T} = \frac{6(1 + n)^2 (\alpha_p - \alpha_g)}{3(1 - \nu_p) (1 + m) (1 + mq) + \left( 1 + \frac{m^3 n}{q} \right) \left( 1 + \frac{q}{mn} \right)} \quad (A-18)$$

This reduces to Eq. (A-11) if Poisson's ratio is zero.

The maximum deflection of a rectangular plate with length  $a$  and width  $b$ , pin-supported at the corners will be approximated by the altitude of a segment of a great circle of a sphere of radius  $r$  bounded by an arc of length  $L = \sqrt{a^2 + b^2}$ , that is

$$\epsilon_{\max} = \frac{L^2}{8r}$$

or

$$\frac{\epsilon_{\max}/h}{\Delta T} = \frac{p^2}{8} \left( \frac{h}{r \Delta T} \right) \quad (A-19)$$

If the origin of polar coordinates is taken at the center of the plate, the deflection of the plate will be given approximately by:

$$\delta = \epsilon_{\max} \left[ 1 - 4 \left( \frac{r}{L} \right)^2 \right] \quad (A-20)$$

where  $r$  is the distance from the center of the plate.

The fiber stress at the top glass surface is the algebraic sum of the flexural stress and normal stress:

$$\sigma = (1 - \nu_g) \left[ \frac{r}{h E_g} - \frac{h}{2r} \right] E_g$$

Using the equations developed for an infinite plate the result was the following expression for stress, which approximates the fiber stress in a rectangular plate at points removed from the edges,

$$\frac{\sigma}{\Delta T} = - \frac{E_g}{1 - \nu_g} \left( \frac{h}{r \Delta T} \right) \left[ \frac{2m^2 + 3m - \frac{9}{mn}}{6(1+m)^2} \right] \quad (A-21)$$

Deflections and stresses are computed in Table A-V for a plate with the dimensions used in the experimental work. The predicted deflections and stresses are also compared with the observed values in Figs. (A-8), (A-9), and (A-10).

## V. CONCLUSIONS

A. Above 40° F, the plastic in a two-ply (glass-plastic) laminate

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Table A-V

THEORETICAL DEFLECTIONS AND STRESSES IN A TWO-PLY (GLASS-PLASTIC) LAMINATED PLATE SUBJECTED TO A UNIFORM CHANGE IN TEMPERATURE

$a = 20 \text{ in.}$   
 $b = 12 \text{ in.}$   
 $L = \sqrt{a^2 + b^2} = \sqrt{(20)^2 + (12)^2} = 23.32 \text{ in.}$   
 $p = L/h = 23.32/0.3075 = 75.84$   
 $\alpha_g = 4.6 \times 10^{-6} \text{ (in/in)/}^\circ\text{F}$   
 $\alpha_p = 63 \times 10^{-6} \text{ (in/in)/}^\circ\text{F}$   
 $E_g = 10 \times 10^6 \text{ psi}$   
 $E_p = 0.21 \times 10^6 \text{ psi}$   
 $h_g = 0.1875$   
 $h_p = 0.1200 \text{ in.}$   
 $\nu_g = 0.23$   
 $\nu_p = 0.40$   
 $h = h_g + h_p = 0.1875 + 0.1200 = 0.3075 \text{ in.}$   
 $m = \frac{h_g}{h_p} = \frac{0.1875}{0.1200} = 1.562$   
 $n = \frac{E_g}{E_p} = \frac{(10)(10^6)}{(0.21)(10^6)} = 47.62$

Formula	Calculation	Result
$q = \frac{1 - \nu_g}{1 - \nu_p} \frac{E_g}{E_p}$	$\frac{1 - (0.23)}{1 - (0.40)}$	1.283
$\frac{h}{r\Delta T} = \frac{6(1+m)^2(\alpha_p - \alpha_g)}{3(1-\nu_p)(1+m)(1+mq) + \left(1 + \frac{m^2n}{q}\right)\left(1 + \frac{q}{mn}\right)}$	$6 \left[ 1 + (1.562) \right]^2 \left[ (63)(10^{-6}) - (4.6)(10^{-6}) \right]$ $(3) \left[ 1 - (0.40) \right] \left[ 1 + (1.562)(1.283) \right] + \left[ 1 + \frac{(1.562)^2(47.62)}{(1.283)} \right] \left[ 1 + \frac{(1.283)}{(1.562)(17.62)} \right]$	$14.49 \times 10^{-6} \text{ (in/in)/}^\circ\text{F}$
$\frac{\delta_{\max}}{\Delta T} = \frac{p^2}{8} \left( \frac{h}{r\Delta T} \right)$	$\frac{(75.84)^2 (14.49)(10^{-6})}{(8)}$	$0.009853 \text{ (in/in)/}^\circ\text{F}$
$\frac{\sigma}{\Delta T} = - \frac{E_g}{(1-\nu_g)} \left( \frac{h}{r\Delta T} \right) \left[ \frac{2m^2 + 3m - \frac{q}{mn}}{6(1+m)^2} \right]$	$(10)(10^6)(1.1875)(10^{-6}) \left[ (1)(1.562)^2 + (3)(1.562) - \frac{(1.283)}{(1.562)(17.62)} \right]$ $\left[ 1 - (0.23) \right] (6) \left[ 1 + (1.562) \right]^2$	$- 45.62 \text{ psi/}^\circ\text{F}$ (Minus sign indicates compressive stresses for temperature increases.)

has a negligible effect on the laminate's thermal-elastic behavior. In particular, negligible deflections and bending stresses will be induced in a laminate subjected to a uniform temperature change above  $40^{\circ}$  F.

B. Below  $40^{\circ}$  F, comparatively large deflections are induced in a two-ply (glass-plastic) laminate by subjecting it to a uniform temperature change. In particular, for a simply supported beam whose ratio of glass thickness to plastic thickness is approximately 1.5 and whose span to total thickness ratio is 65, the maximum deflection observed experimentally was 0.0056 inch per inch of plate thickness per degree of temperature change. For a rectangular plate, pin-supported at the corners and with the same thickness ratio as the beam but with a diagonal span to total thickness ratio of 75, the maximum deflection observed experimentally was 0.0088 inch per inch of plate thickness per degree of temperature change. In the case of both the beam and the plate, the deflection surface was approximately the cap of a sphere.

C. The fiber stresses in the glass layer of a two-ply laminate vary slightly over its length (and width). For a beam with the shape and thickness ratios given in B, the average fiber stress observed on the top glass surface was 26 psi per degree temperature change. For the plate with the dimension ratios given above, the maximum fiber stress on the top glass surface was approximately 50 psi per degree temperature change.

D. When a two-ply laminate is subjected to a temperature change below  $40^{\circ}$  F, a concentration of normal stress arises along the glass-

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plastic interface at the corners of the specimen. For the test beam described in B a temperature decrease of  $60^{\circ}$  F was sufficient to cause failure.

E. In a beam having one rough and one polished edge, large but gradual temperature changes initiated cracks in the glass at the rough edge with no failure in the bond. Further temperature changes produced a 1/8-inch bond failure on the polished edge before failure of the glass occurred. In general the bond shows greater strength at low temperatures than the glass.

F. The deflections and average fiber stresses in a two-ply laminate can be predicted adequately by the theory developed by S. Timoshenko for application to bimetallic thermostats. The theory predicts that the deflection surfaces of simply supported beams and plates will be spherical caps. The maximum deflection as predicted by the theory is directly proportional to the total thickness of the laminate, to the change in temperature, and to the square of the length of span to thickness ratio. The deflection also depends in a complicated manner on the ratio of glass thickness to plastic thickness. The small discrepancy between experimental and predicted values is probably due to the difficulty in obtaining representative values of the temperature-dependent elastic constants of the plastic for use in the theoretical calculations.

The theory predicts that the fiber stresses will be constant along the beam, and the numerical values predicted compare with the average experimental stresses; however, the stress concentration in the actual beams causes a non-uniform distribution of the fiber stress along

the beam and over the plate. Hence, the observed maximum and minimum stresses were above and below the average values.

VI. CONTRIBUTING PERSONNEL

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Associate Research Engineer

APPENDIX B

PHOTOELASTIC STUDIES OF TWO- AND THREE-PLY LAMINATES

SUBJECTED TO UNIFORM TEMPERATURE CHANGES

ARMOUR RESEARCH FOUNDATION OF ILLINOIS INSTITUTE OF TECHNOLOGY

Project No. 90-692J

Report No. 36

## APPENDIX B

### PHOTOELASTIC STUDIES OF TWO- AND THREE-PLY LAMINATES

#### SUBJECTED TO UNIFORM TEMPERATURE CHANGES

##### I. INTRODUCTION

In general, a shear stress distribution will exist at the interface between two materials at any temperature other than the one at which they were bonded together. The magnitude and distribution of this stress will depend upon the change in temperature, the coefficients of thermal expansion of the two materials, their relative stiffness and, in the case of those materials having time-dependent stress-strain curves, on the time after bonding. In the case of laminated windshields, it is probable that the shear stress on the interface practically vanishes after a few days due to the stress-relaxation properties of the highly plasticized polyvinyl butyral plastic.

The nature of the shear stress distribution and its dependence on the factors listed are far from simple. The only available theoretical work is a paper by B. J. Aleck\* which gives an approximate solution for the case of a semi-infinite plate clamped along one edge to an infinitely rigid material of infinite extent. This solution contains approximations which render it inaccurate in exactly that region where the predicted stress is highest. Therefore, it was decided to determine the stress distribution at the interface of two- and three-ply laminates by photoelastic methods.

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\*B. J. Aleck, "Thermal Stresses in a Rectangular Plate Clamped Along an Edge", Journal of Applied Mechanics, vol. 16, June 1949, p. 118

## II. TEST PROCEDURE

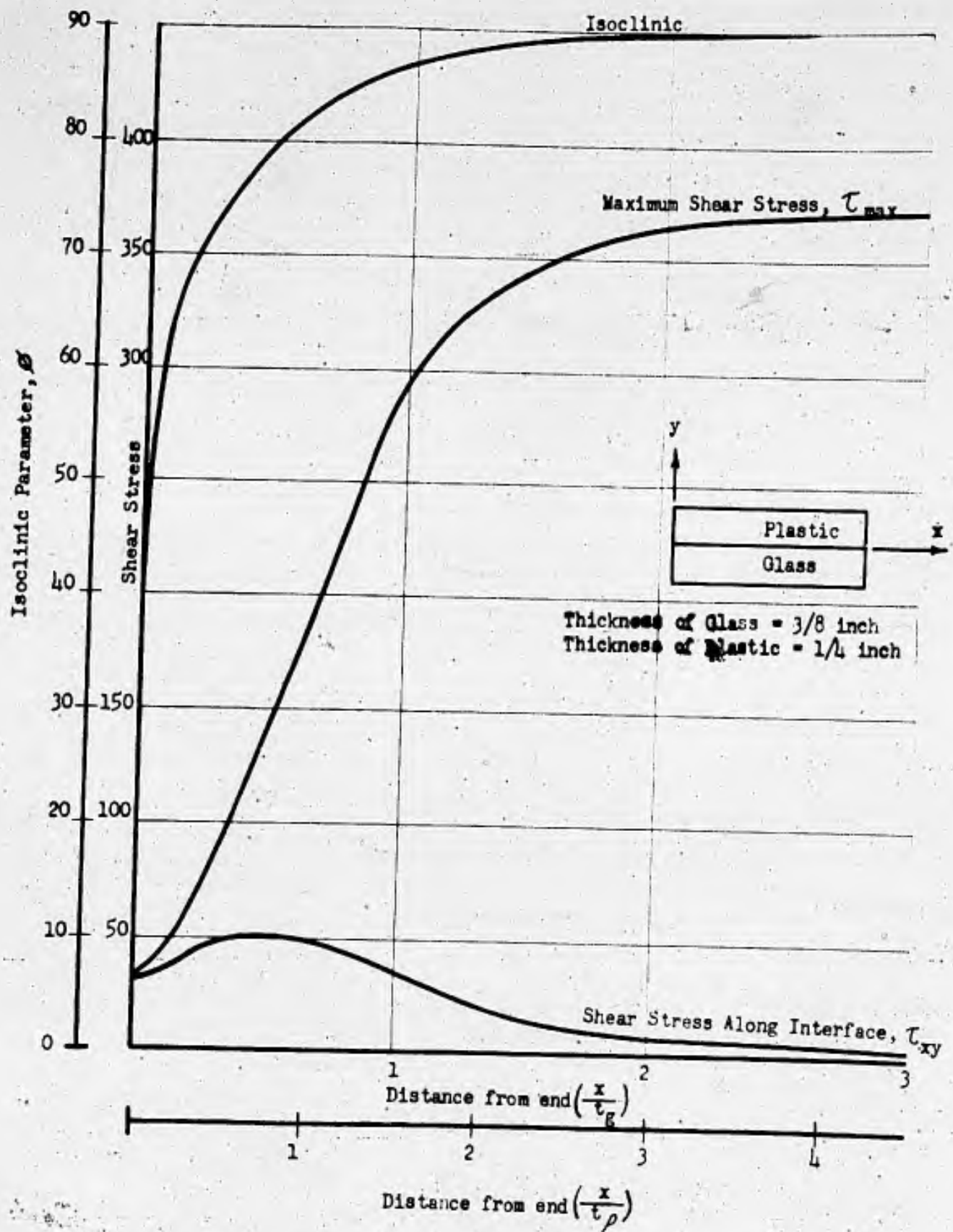
The test pieces were two- and three-ply laminates, measuring 2 in. by 12 in. in the plane of the glass. The thickness of glass and plastic were varied from specimen to specimen. The term, "two-ply laminate", as used in this Appendix, refers to a single piece of plastic adhering to a single piece of glass. Three-ply laminate designates a glass-plastic-glass sandwich. The test pieces were placed in a chamber having double walls of selected annealed glass through which the polarized light beam could pass. This chamber was so arranged that either heated or cooled air could be circulated through it to maintain the desired test temperature. Temperatures in the range of  $+10^{\circ}$  F to  $+20^{\circ}$  F were found to be necessary for testing the two-ply laminates, since higher values did not produce sufficient stress to permit an accurate determination and lower ones risked failure of the specimen by chipping of the glass, delamination, or both. Lower temperatures were used for the three-ply laminates.

## III. DISCUSSION

All of the data necessary for the determination of the shear stress distribution on the glass-plastic interface are readily determined photo-elastically. The circular polariscope gives the loci of points (isochromatic fringes) where the maximum shear stress has certain values which depend on the physical constants of the material, and the plane polariscope shows the isoclinics or loci of points where the directions of the principal stresses coincide with the principal directions of the polariscope (which may be rotated to cover all possible directions).

For the purpose of these tests it was found more convenient to sketch the isochromatics and isoclinics than to record them photographically; results for the two-ply laminate are shown in Fig. B-1. Perhaps the most striking feature of these results is the fact that the indicated values are extremely low, much lower than would be expected from the fact that the glass is known to fail at temperatures only 10 or 15 degrees lower. Two possible explanations might be advanced: from the fact that failure by chipping of the glass seems to occur at higher temperatures when there is reason to suspect the quality of the bond between plastic and glass, it might be assumed that there are isolated spots of good bond which carry the entire load, thus producing local stresses which are high enough to cause glass failure while the average stress seen by the polariscope remains very small. More probable, however, is the hypothesis that the stress distribution is such that the directions of the principal stresses in the glass change markedly from layer to layer along the optical axis of the polariscope. Such stress distributions are not suitable for examination by the usual techniques of two-dimensional photoelasticity.

Several attempts were made to obtain information similar to that shown in Fig. B-1 for three-ply laminates, but in every case difficulty was encountered with the isoclinics. A beam made up of two plates of 3/8-in. glass separated by 3/8 in. of plastic was finally tried in the hope that the larger dimension would permit a more accurate determination of the isoclinic pattern. During this test it became apparent that the isoclinics were changing positions as the temperature was lowered. At some temperatures they became blurred and indistinct and finally vanished.



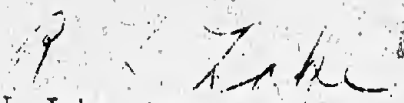
**Fig. B-1** ISOCLINIC PARAMETER AND SHEAR STRESS DISTRIBUTION IN TWO-PLY (GLASS-PLASTIC) LAMINATE OBTAINED FROM PHOTOELASTIC TESTS

(Data taken when the beam was at a uniform temperature of 20° F. below a 40° F. reference temperature.)

altogether. On the basis of this evidence it is necessary to conclude that the directions of the principal stresses do change from layer to layer and that the photoelastic method cannot be used with specimens as thick as 2 in. in the direction of light propagation. Some idea of the distribution in the central region of a long edge might possibly be gained by examining a thin (say  $3/8$ -in. in the direction of light propagation) slice of a laminate.

IV. CONTRIBUTING PERSONNEL

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APPENDIX C

SHEAR TESTS ON THREE-PLY (GLASS-PLASTIC-GLASS) LAMINATES

ARMOUR RESEARCH FOUNDATION OF ILLINOIS INSTITUTE OF TECHNOLOGY

Project No. 90-692J

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## APPENDIX C

### SHEAR TESTS ON THREE-PLY (GLASS-PLASTIC-GLASS) LAMINATES

#### I. OBJECTIVE

The objective of these tests was to obtain some measure of the strength of a three-ply (glass-plastic-glass) laminate under the action of shear stresses at the glass-plastic interface.

#### II. METHOD

A number of laminated specimens were made for these tests; each was composed of two pieces of plate glass, 2-1/2 by 2-1/2 by 3/16 in., with a thin layer (0.020 in. thick) of polyvinyl butyral plastic laminated between them. Both glass and plastic were supplied by the Libbey-Owens-Ford Glass Company. The first specimens were made with a large circular bonded area. With improved laminating controls, the capacity of the torque machine to fracture these specimens was exceeded; hence, a smaller circular ring area was used for further tests. Satisfactory bonding results were obtained by placing the specimens under mechanical pressure in an electric oven at 275° F for about 30 minutes.

Each laminated specimen was held in grips as shown in Fig. C-1. A strip of cardboard was inserted between the edges of the glass plates and the metal frame to reduce possible stress concentrations. The grips were mounted in the torque machine, one of the grips being attached to the head shaft, the other to the tail shaft of the machine, the distance between the grips approximately corresponding to the thickness of the plastic. The grips were rotated with respect to each other by the machine, producing a torque at the bonded area.

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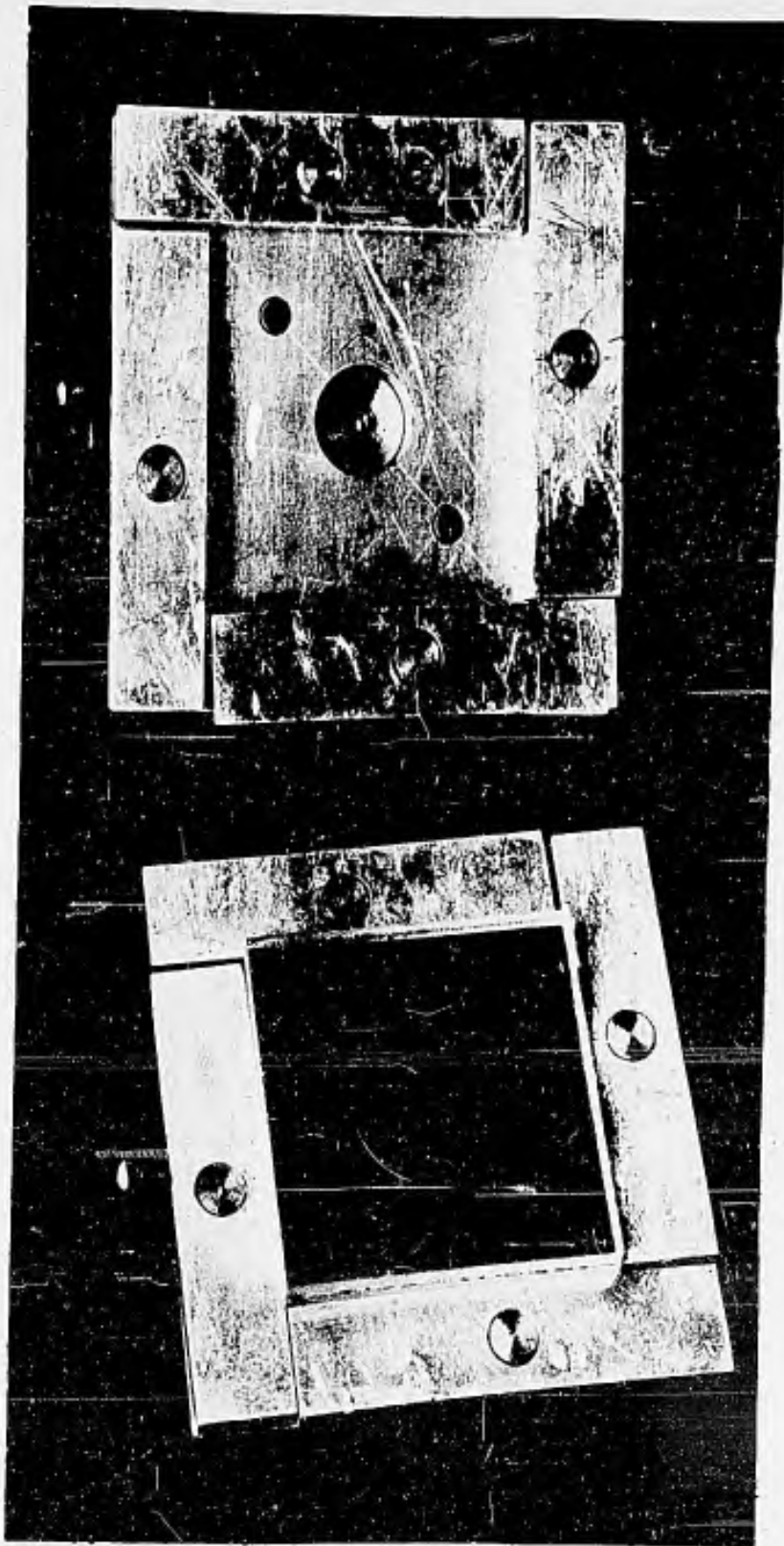


FIG. C-1 GRIPS FOR HOLDING SPECIMEN

The torque capacity of the machine is low. A worm gear drive is utilized to apply a torsional load to the specimen, and the torque is measured by means of a pendulum acting through a series of levers. Figures No. C-2 and C-3 are photographs of the machine.

An insulated chamber, made of Celotex, was built around the specimen and the grips. A blower, to circulate thermostatically controlled air, was attached to the chamber.

The specimens were mounted in the machine and the blower was started. Upon reaching thermal equilibrium at the desired test temperature, torque was gradually applied until a sudden drop in the indicated torque announced failure of the specimen. The torque preceding failure was recorded, and the specimen was removed from the chamber. Fractured specimens were subsequently photographed.

### III. RESULTS

The torsional shear stress at the outermost fiber of the interface corresponding to the torque at fracture was calculated and the results are shown in Column 7 of Table C-I. Values in this column represent the highest value of the shear stresses at the interface resisting the torque between glass and plastic. The maximum tensile stress in the glass is at an angle of  $45^\circ$  to the interface and its magnitude is equal to that of the maximum shear stress. The tensile strength of annealed glass under tension (modulus of rupture) is approximately 6500 psi; the ratio between this value and the maximum tensile stress due to the applied torque is shown in Column 8.

Photographs of the fractured specimens are shown in Fig. C-4 and an enlarged photograph of specimen No. 5 appears in Fig. C-5. It will be

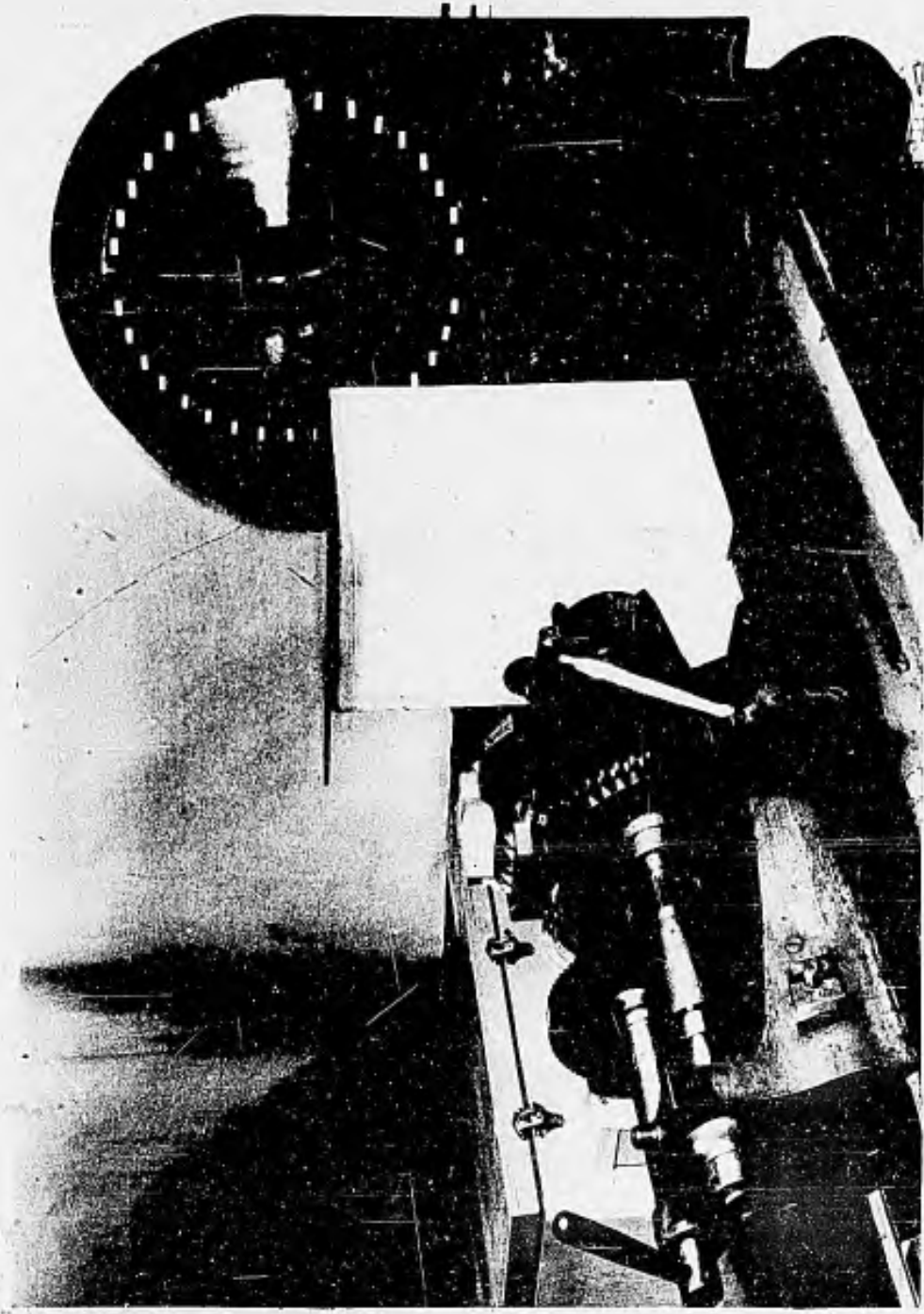


FIG. C-2 SET-UP OF APPARATUS

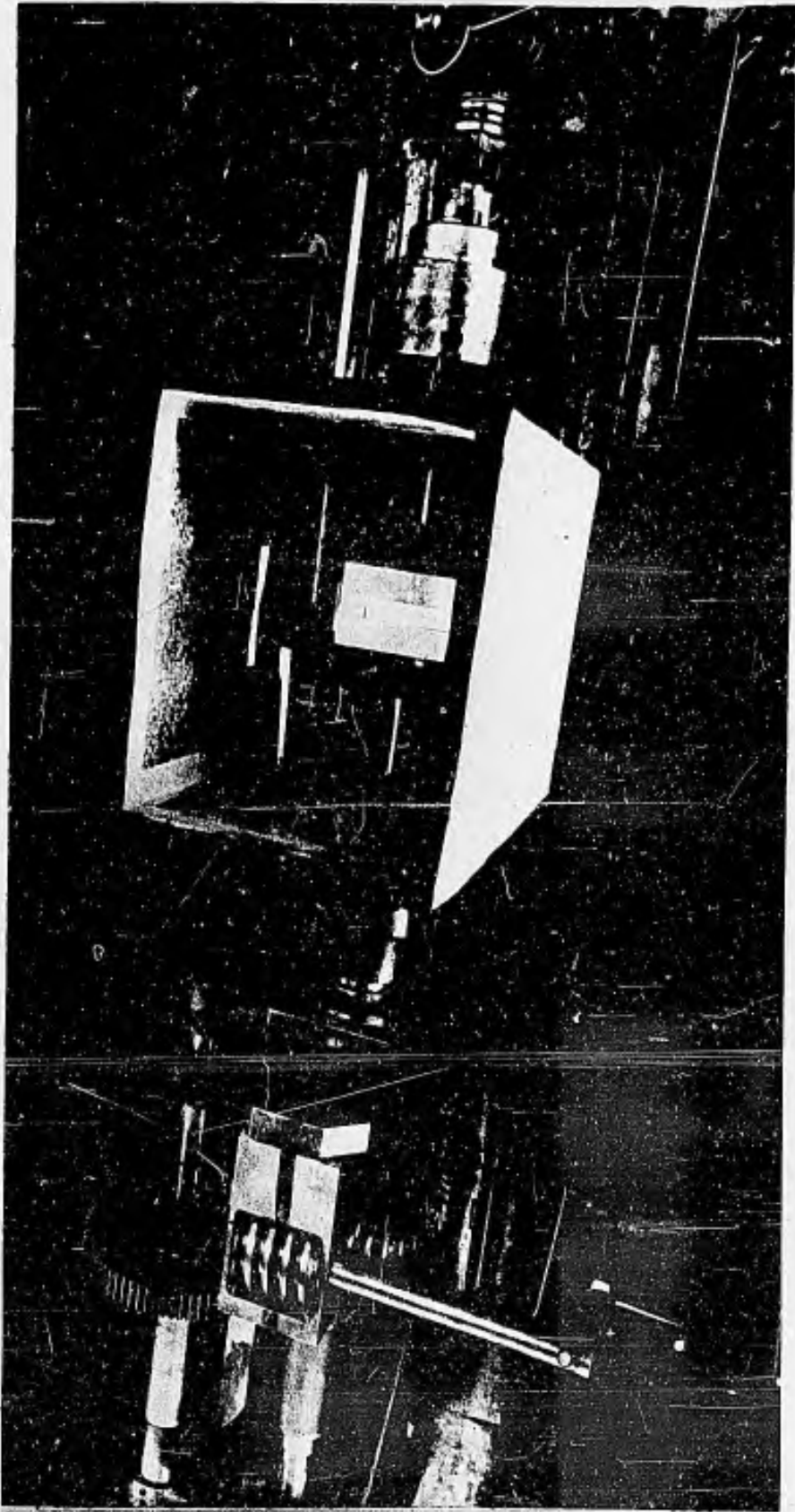


Fig. C-3 TOP VIEW OF APPARATUS

Table C-I  
RESULTS OF SHEAR TESTS ON THREE-PLY LAMINATES

(1) Specimen No.	(2) Bonded area (a) (circular ring) in. Dia.	(3) Method of bonding	(4) Bonded area (b) (circular ring) in. Dia.	(5) Temperature (shear test) °F	(6) Shear load in. lb	(7) (S <sub>s</sub> ) <sub>max</sub> psi	(8) (S <sub>n</sub> ) <sub>max</sub> (S <sub>s</sub> ) <sub>max</sub>
A	1-1/4 (circular area)	autoclave	1-5/16 (circular area)	30	540	1216	5.4
B	1-1/4 (circular area)	electric oven	1-7/16 (circular area)	70	600	1029	6.3
1	1-3/4 - 1-1/4	autoclave	2-1/8 - 1/2	70	765 (pin sheared)		
4	1-3/4 - 1-1/4	electric oven	1-7/8 - 1-1/8	46	3000 (no fracture)	2662	2.4
5	1-1/2 - 1-1/4	electric oven	1-5/8 - 1-1/8	54	1490	2295	2.8
6	1-1/2 - 1-1/4	electric oven	1-5/8 - 1-1/8	50	1840 (c)	2834	2.2

(a) Dimensions before bonding took place.

(b) Dimensions after bonding took place.

(c) Specimen was removed for inspection from torque machine when torsional load of 1280 in. lb was reached. There was a crack in one layer of Glass apparently caused by the concentration of stress at the pivot pin of the self-adjusting jaws of the specimen holder.

$$(d) (S_s)_{max} = \frac{16 M_t}{\pi d_o^3 \left(1 - \frac{d_i}{d_o}\right)}, \text{ where } (S_s)_{max} = \text{maximum shear stresses, psi}$$

$$M_t = \text{applied torque, lb in.}$$

$$d_i = \text{inside diameter, in.}$$

$$d_o = \text{outside diameter, in.}$$

$$(e) (S_n)_{max} = 6500 \text{ psi.}$$



4



5



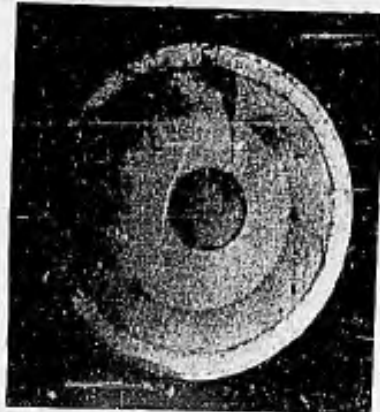
6



A



B



1

FIG. C-4: FRACTURED SPECIMENS



5

Fig. C-5 SPECIMEN No. 5

c- 9

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noted that specimens No. A, B, 5, and 6 have cracks running from edge to edge. Such fractures probably result from stress concentrations at the edge of the glass plates, due to the action of the holder. If the drop in torque occurred when these fractures originated, the recorded values of torque have little significance for the shear strength of the laminate.

Most of the specimens removed from the machine fell apart after the test. In several specimens part of the plastic separated from one of the glass plates, while another portion of the plastic separated from the other glass plate; in others, separation from both plates occurred, a strip of plastic remaining free. In nearly all instances the plastic was covered by a multitude of glass chips so that it was difficult to determine whether any separation had occurred at the interface. Most fractures occurred in the glass, sometimes extending to a considerable depth into the plate. It was not possible to determine the angle with respect to the interface at which the origin of such a fracture was oriented. In general, it was not possible to determine how these fractures originated, so that it is difficult to determine the significance of the measured maximum shear stresses.

#### IV. CONTRIBUTING PERSONNEL

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APPENDIX D

RESISTANCE TO FAILURE OF LAMINATED BEAMS  
SUBJECTED TO A UNIFORM DROP IN TEMPERATURE

ARMOUR RESEARCH FOUNDATION OF ILLINOIS INSTITUTE OF TECHNOLOGY

Project No. 90-692J

Report No. 36

## APPENDIX D

### RESISTANCE TO FAILURE OF LAMINATED BEAMS SUBJECTED TO A UNIFORM DROP IN TEMPERATURE

#### I. OBJECTIVE

Two by 12 in., two- and three-ply laminated beams, employing several combinations of annealed, tempered, and filmed (electrically conductive coated) glass of various thicknesses, were tested under three cold-soak conditions to determine qualitatively the effect of these parameters on the resistance to failure of the laminate.

#### II. TEST SPECIMENS AND PROCEDURE

##### A. General Description of Tests

During the first test, the beams were placed in a controlled-temperature chamber and the temperature was varied slowly so as to maintain the specimens at nearly thermal equilibrium. The purpose of this test was to produce failure under pure cold-soak conditions, thus producing stresses due to uniform temperature changes of the laminated beams. Very few failures occurred in the 70 to -100° F range of this test; therefore, the attempt to observe failure due to cold-soak conditions under thermal equilibrium was discontinued. Other tests were devised to determine the comparative resistance to failure under less clearly defined loading conditions.

The second test also was performed in the controlled-temperature chamber, but the temperature was varied as quickly as possible in the hope that more rapid imposition of the thermal gradients in the test beams would

produce failure more readily. The temperature range was again 70 to -100° F and, as in the first test, very few failures were observed.

During the third test, alcohol baths at various temperatures were used to quench the beams from room temperature to successively lower temperatures. This test produced failures in an appreciable number of the beams.

The specimens employed in the above tests are described in Table D-I.

B. Apparatus

1. Test No. 1

Test No. 1 was performed in a Bowser controlled-temperature unit. This unit is comprised of an insulated chamber (whose interior is visible through a glass window located on one side), an air-circulating system, heating coils, a refrigeration system, and a temperature-control system. The temperature in the chamber was measured by thermometers at two locations, while the temperature at the center of the thickest beam was measured by a thermocouple in specimen No. 17. To observe attainment of steady-state conditions in the beams, readings were taken on Westinghouse sensing elements located in the plastic core of several specimens. While these readings were not interpreted as temperatures, steady-state conditions were assumed to exist when the resistance of the sensing elements showed no change for several successive readings. Special racks were constructed for supporting the specimens; Fig. D-1 shows the arrangement of the specimens in the chamber.

Table D-I

## DESCRIPTION OF TEST SPECIMENS

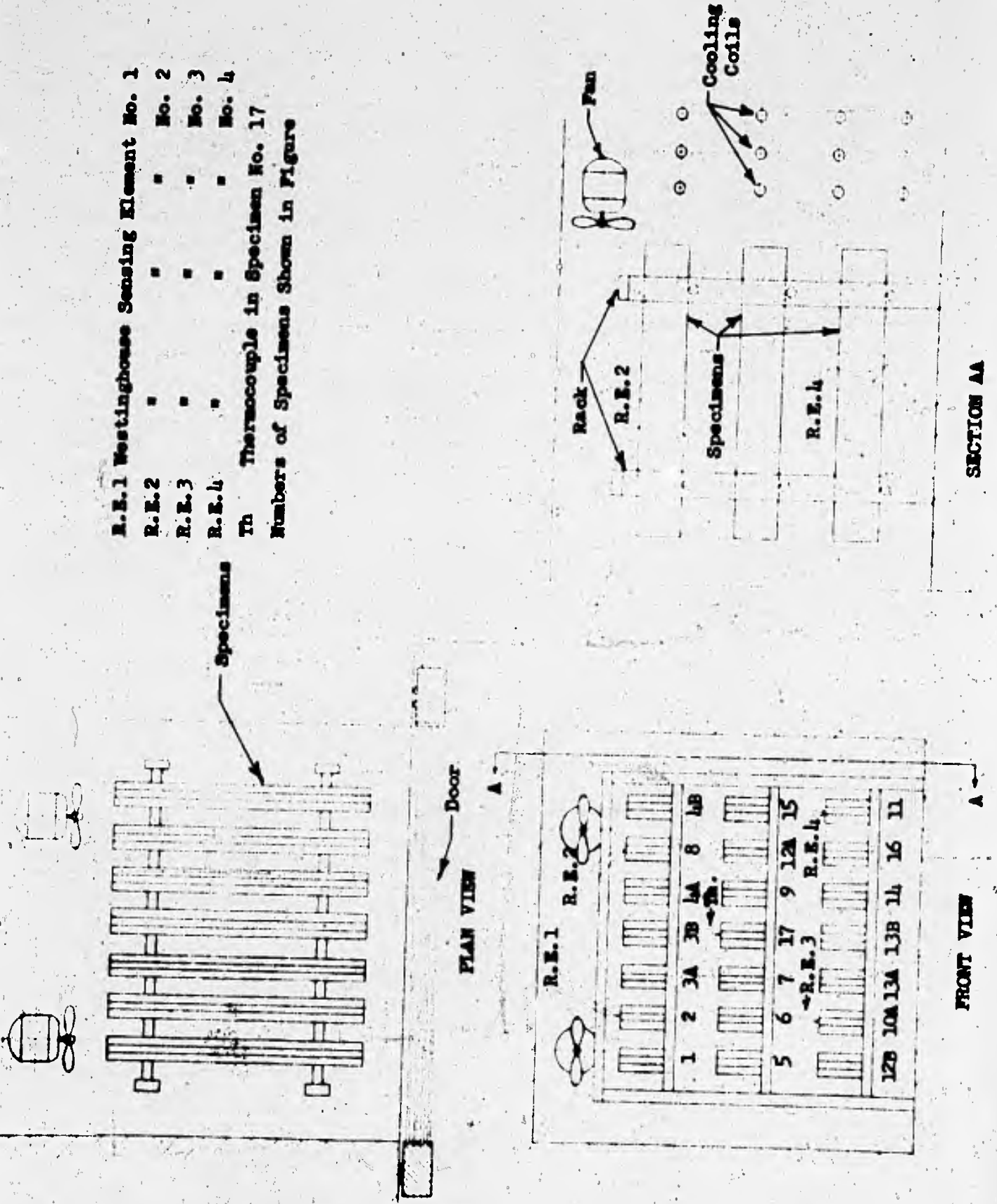
Specimen No.	Manufacturer	ARF Dwg. No.	Description
<u>1. Two-Ply Beams</u>			
1	Glass Companies*	17D3-003	13/64-in. annealed glass, 1/8-in. plastic
2	Glass Companies	17D3-004	13/64-in. filmed glass, 1/8-in. plastic
<u>2. Three-Ply Beams</u>			
3	Glass Companies	17D3-006-1	13/64-in. annealed glass (2 plates) 1/8-in. plastic
4	Glass Companies	17D3-006-3	13/64-in. annealed glass, 3/8-in. annealed glass, 1/8-in. plastic
5	ARF**	ARF No. 7	13/64-in. annealed glass (2 plates) 0.26-in. plastic
6	ARF	ARF No. 8	13/64-in. annealed glass (2 plates) 0.12-in. plastic
7	ARF	ARF No. 9	13/64-in. annealed glass (2 plates) 0.020-in. plastic
8	Glass Companies	17D3-005-1	13/64-in. filmed glass, 13/64-in. annealed glass, 1/8-in. plastic
9	Glass Companies	17D3-005-3	13/64-in. filmed glass, 3/8-in. annealed glass, 1/8-in. plastic
10	Glass Companies	17D3-005-2	13/64-in. filmed glass, 13/64-in. fully tempered glass, 1/8-in. plastic
11	Glass Companies	17D3-005-A	13/64-in. filmed glass, 3/8-in. fully tempered glass, 1/8-in. plastic
12	Glass Companies	17D3-006-2	13/64-in. fully tempered glass, 13/64-in. annealed glass, 1/8-in. plastic
13	Glass Companies	17D3-006-4	3/8-in. fully tempered glass, 1/4-in. annealed glass, 1/8-in. plastic
14	ARF	ARF No. 10	13/64-in. filmed glass (2 plates), 13/64-in. plastic
15	ARF	ARF No. 2	13/64-in. fully tempered glass (2 plates), 13/64-in. plastic
16	ARF	ARF No. 3	13/64-in. filmed glass (2 plates), 13/64-in. plastic
17	ARF		Thermocouple specimen, 3/8-in. fully tempered glass (2 plates), 3/8-in. plastic

\*"Glass Companies" refers to specimens supplied by either Pittsburgh Plate Glass Co. or Libbey-Owens-Ford Glass Co.

\*\*ARF refers to specimens produced in the ARF laboratory autoclave.

- R.E.1 Westinghouse Sensing Element No. 1
- R.E.2 " " " No. 2
- R.E.3 " " " No. 3
- R.E.4 " " " No. 4

The Thermocouple in Specimen No. 17  
 Numbers of Specimens Shown in Figure



**Fig. B-1 ARRANGEMENT OF SPECIMENS IN BOWSER UNIT**

**FOR TESTS NO. 1 AND 2**

## 2. Test No. 2

Test No. 2 was also performed in the Bowser unit. The arrangement shown in Fig. D-1 was used, except that specimen No. 8 was replaced by specimen No. 2.

## 3. Test No. 3

Cold alcohol was employed as the cooling medium in Test No. 3. To obtain the desired low temperatures, dry ice was dissolved in alcohol in a 55-gallon drum insulated with Calotex. Three rectangular, woven wire baskets were constructed to hold the beams in the drum; thermocouples were attached to the baskets to measure the temperature of the bath in the vicinity of the beams. Westinghouse sensing elements again were used to obtain a qualitative measure of the rate of temperature change in the interior of the specimens. The arrangement of the specimens and thermocouples is shown in Fig. D-2.

## C. Test Procedure

### 1. Test No. 1

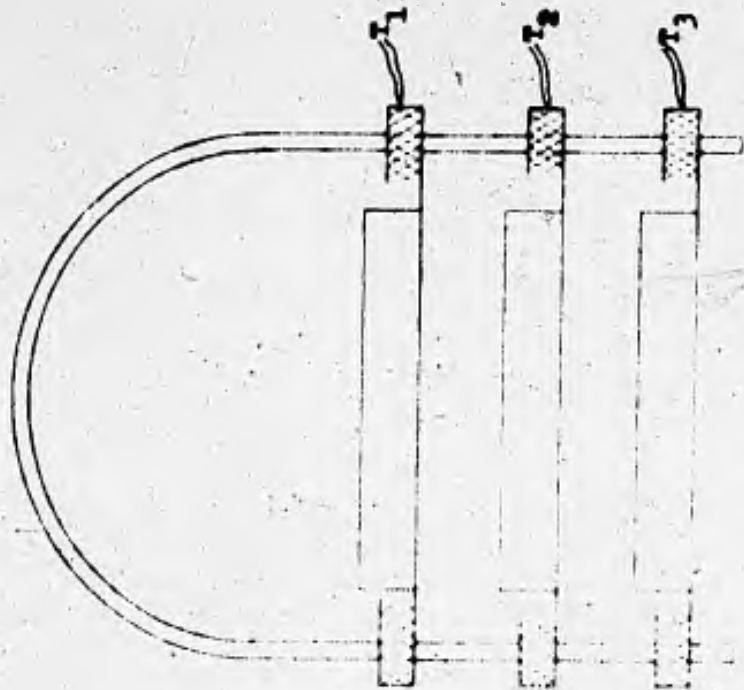
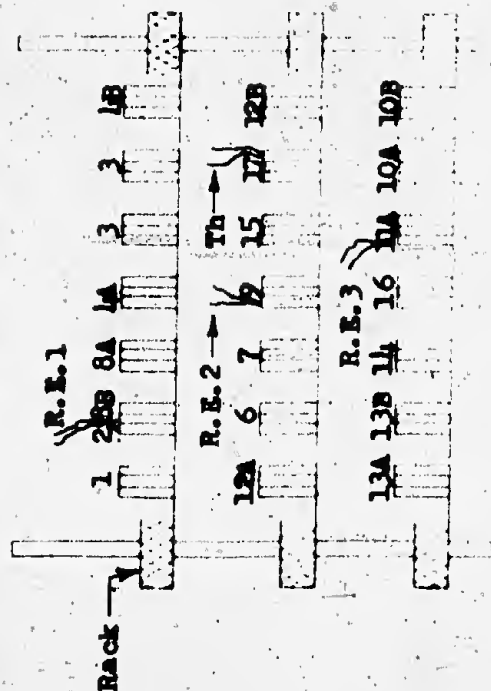
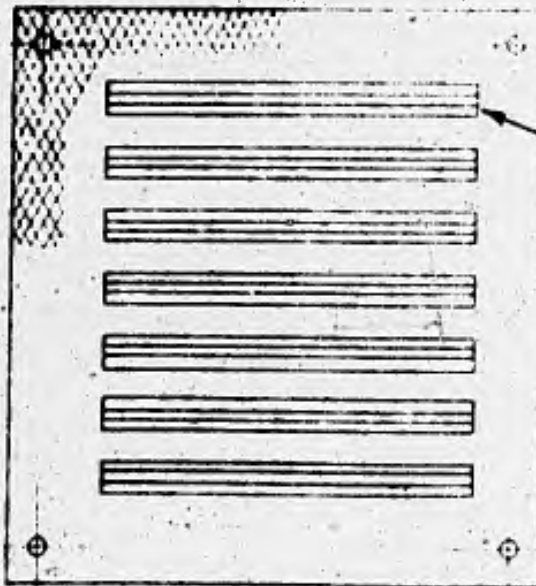
The test chamber was brought to equilibrium at 30° F. Then, the temperature was lowered 10° F at a time, and the chamber was maintained at each temperature until steady-state conditions were observed on thermocouples and Westinghouse sensing elements for a period of 30 minutes. Maximum temperature differences within the chamber were observed to range from 5° to 10° F, as recorded by top and bottom thermometers. The lowest temperature reached during this test was -98° F. At the conclusion of the cooling test, the chamber was brought back to room temperature. Failures obtained during this test were observed, recorded, and photographed.

R.E.1 Westinghouse Sensing Element No. 1  
 R.E.2 " " " " No. 2  
 R.E.3 " " " " No. 3

T<sub>1</sub> Thermocouple No. 1  
 T<sub>2</sub> " " No. 2  
 T<sub>3</sub> " " No. 3

T<sub>0</sub> Control Specimen

Specimen Numbers Shown in Figure



**FIG. D-8 SPECIMEN RACK AND ARRANGEMENT OF SPECIMENS IN TEST NO. 3**

## 2. Test No. 2

The chamber was brought to equilibrium at room temperature (80° F). The thermostat was set for -100° F and the temperature in the chamber was dropped to -94° F within 3-1/2 hours (48.6° F/hr). Temperatures were recorded by thermometers at the top and bottom of the chamber, a thermocouple in the center of the core of specimen No. 17, and Westinghouse sensing elements located as shown in Fig. D-1. As in Test No. 1, all failures produced during this test were observed, recorded, and photographed.

## 3. Test No. 3

The alcohol baths previously described were prepared at several degrees below the desired final temperature. After the specimens had been brought to equilibrium at room temperature, the rack supporting them was suddenly immersed in the bath, and time-temperature readings were recorded. Temperature readings were obtained by: (a) thermocouples freely suspended in the alcohol bath at each level of the rack, (b) a thermocouple in specimen No. 17, and (c) Westinghouse sensing elements in several beams.

A specimen containing a sensing element was located at each level of the rack, and the attainment of steady-state conditions was noted. The temperature of the bath was checked frequently by thermometers immersed in the alcohol. The specimens were kept in the bath until steady-state conditions were achieved for 5 min. The specimens were then removed and allowed to reach equilibrium with the ambient room temperature while another bath was prepared.

All specimens were subjected to close visual examination and damage was recorded after each immersion. Tests were conducted with alcohol baths at the following temperatures: 0, -10, -22, -34, -37, -49, -64, -76, -86, -102, and -112° F. In each instance, all of the specimens were at room temperature before immersion.

Specimens No. 3-A, 6, 12-A, and 13-A were taken apart by the following procedure: The beam was sawed in two through the plastic core parallel to the faces of the glass panes. The plastic was peeled off the glass panes after soaking in hot alcohol. The glass panes were then studied and photograms were taken employing the technique described in Appendix A of this report.

In specimens where separation of glass and plastic had taken place or where fracture or a chipping type of separation of the glass panes had occurred, the broken parts and fragments were collected and photograms were taken of the plastic core and of the chipped glass panes. Specimens which had been damaged locally, and which had not been taken apart, were photographed by the same technique without further preparation.

The same specimens were used in all three tests; however, in Test No. 3, all specimens destroyed in the course of one immersion were replaced for the succeeding immersion, and several duplicate specimens were replaced by new beams for immersion at -80° F. The fact that these specimens were subjected to repeated cycles of stress and stress relief probably affected their behavior in each successive test. This may account in part for the different behavior of the beams which were immersed for the first time at -80° F.

### III. FAILURES OF TWO-PLY BEAMS

A two-ply beam constructed with annealed glass failed in each of the three tests. One two-ply beam constructed with filmed glass failed in Tests No. 1 and 3, and two such beams failed in Test No. 2. The temperature at failure was not recorded in Test No. 3 since further data on failure temperatures of two-ply beams were considered unnecessary. Specimens are described in Table D-II, together with observed failures. Failures produced in previous tests also are included in this table for comparison purposes.

The failures of all two-ply beams were similar, except that bond failures of varying extent were observed in all beams. All failures occurred partly at the interface and partly through the glass, parallel and near to the interface. Fracture through the glass began with a few cracks at or near one of the edges (in most cases at the long edges) and moved toward the interior of the beam, the individual fractures growing and merging with other fractures to form a crack-front of increasing length.

Figure D-3 is a photogram of a fracture in an annealed two-ply beam (specimen No. 1). It shows a typical fracture of annealed two-ply beams. The surface markings of a fracture are always significant. The long curved lines (rib lines) are perpendicular to the direction of motion of the fracture. They represent crack propagation fronts and indicate the direction in which the fracture moves. The short straight lines (hackle marks) are small peaks on the glass surface and may represent the edges at small individual fractures. It can be seen that most of the fracture origins are located close to the edge, several appearing on the bevel of the beam, although a few of the fractures originated some distance from

**Table D-II**  
**FAILURES OF TWO-PLY BEAMS**

Type of Test	Specimen No. and Manufacturer	Specimen Description	Temperature °F	Description of Failure
<u>1. Laminates Constructed with Annealed Glass</u>				
No. 1	1-A (a) Glass Co.	13/64 in. glass 1/8 in. plastic	-30 -64	Chipping failure, started at long edge Chipping failure, 80 per cent complete
No. 2	1-B Glass Co.	13/64 in. glass 1/8 in. plastic	-32 -45	Chipping failure, started at long edge Chipping failure, nearly complete
No. 1	C Glass Co.	20 x 3 in. beam 13/64 in. glass 1/8 in. plastic	-25 -50	Chipping failure, started at corner of beam Chipping failure, 80 per cent complete
No. 1	D ARF	2 x 12 in. beam 3/8 in. glass 1/8 in. plastic	-5 to -10	Chipping failure, started at long edge
No. 1	E ARF	2 x 12 in. beam 1/8 in. glass 1/8 in. plastic	-5 to -10	Chipping failure, started at long edge
No. 1	F Glass Co.	20 x 12 in. plastic 1/4 in. glass 1/8 in. plastic	-50	Chipping failure, started near corner
<u>2. Laminates Constructed with Filmed Glass</u>				
No. 1	2-A Glass Co.	13/64 in. glass 1/8 in. plastic	-1	Chipping failure, started at short edge
No. 2	2-B Glass Co.	13/64 in. glass 1/8 in. plastic	-21	Chipping failure, started at long edge
No. 2	2-C Glass Co.	13/64 in. glass 1/8 in. plastic	-56	Chipping failure, started at long edge

(a) -A, -B, -C, ... indicate 1st, 2nd, 3rd, ... replacements of the specimen type numbers which they follow.

Fig. E-3

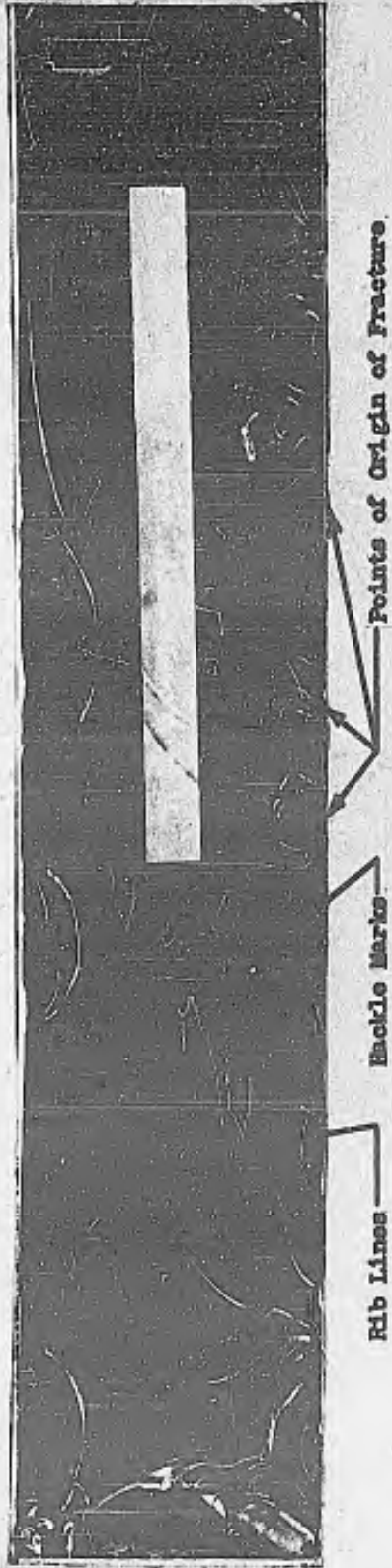


FIG. D-3 PHOTOGRAM OF FRACTURE SURFACE OF ANNEALED GLASS PANE (SPECIMEN NO. 1, TEST NO. 1)

the edge of the glass. Some delamination between glass and plastic is apparent near one edge.

All of the two-ply beams tested in the course of this experiment were supplied by the glass companies (LOF and PPG). The edges of these specimens were beveled and polished. Appendix A of this report describes tests of glass beams which had both sawed and beveled edges; in these beams fractures at the sawed edges started at a higher temperature than those at the beveled edges.

The points of origin of the fractures were subjected to close examination. It appears that the first small cracks started at a very shallow angle to the interface. This indicates the existence of critical tensile stresses normal to the interface.

A fracture through the glass of a two-ply beam constructed with filmed glass is shown in Fig. D-4. The appearance of the fracture is similar to that shown in Fig. D-3, except that the areas of delamination are more extensive. The spacing of rib marks is somewhat closer, which is typical of failures in tempered glass.

All failures of two-ply beams observed during these tests were identical to those shown in Figs. D-3 and D-4, with the exception of a two-ply beam made with filmed glass which showed an extensive bond failure during Test No. 3.

The failures of annealed beams observed during these tests seem to be reproducible; however, the evidence probably is not sufficient to draw conclusions about the effect of beam design upon its failure. The failures of two-ply beams made with filmed glass apparently are not reproducible.

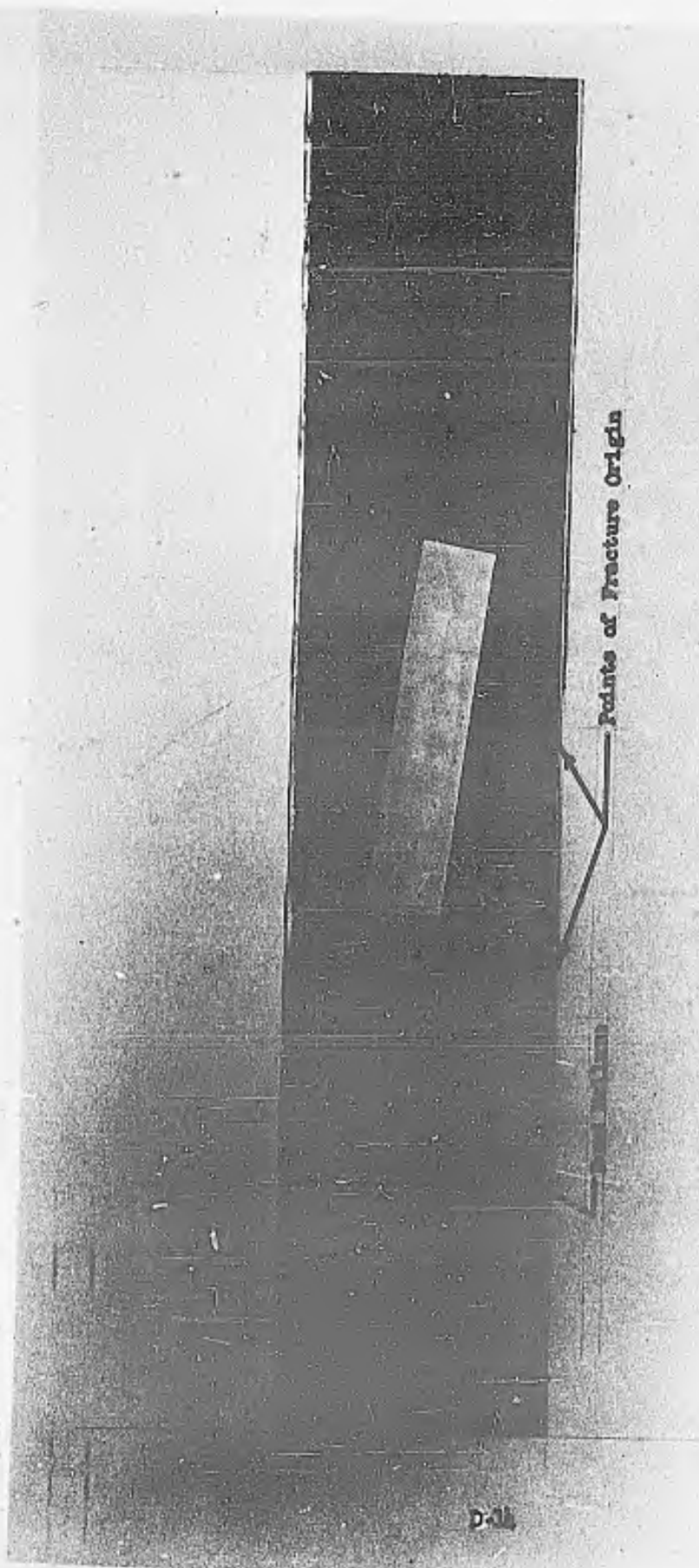


FIG. D-4. PHOTOGRAPH OF FRACTURE SURFACE OF FILMED GLASS PANE (SPECIMEN NO. 2, TEST NO. 1).

D-4

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#### IV. FAILURES OF THREE-PLY BEAMS

##### A. General Discussion of Failures

With the exception of specimen No. 5, no damage occurred in any of the three-ply beams during Tests No. 1 and 2. Damage in these beams was produced only by quenching them in cold alcohol in Test No. 3.

Failure may have occurred only under very rapid cooling because of the stresses induced by high thermal gradients, or because of the effect of the cooling rate on the deformation under stress of the plastic. The deformation of the plastic under stress depends on the rate of loading at all temperatures, its creep rate decreasing rapidly at lower temperature. It is likely that the thermal stresses in three-ply beams would be higher under rapid cooling than under slow cooling, due to the suppression of plastic creep by quenching.

Since nearly all failures took place at the interface of the beam where stresses due to uniform temperature changes were most severe, it seems likely that these stresses, rather than stress due to temperature gradients, are responsible for the failures, and that suppression of plastic creep by quenching accounted for the failure of beams in Test No. 3 but not in Tests No. 1 and 2.

Failures observed in three-ply beams are shown in Tables D-III, D-IV, and D-V. Beams of all designs were damaged during Test No. 3. In most cases, damage was confined to narrow regions near the edges; however, in some of the specimens major portions of one or both glass panes fractured and/or separated from the plastic. Some of the beams which were destroyed in the course of the tests showed evidence of slight local damage before failure occurred. On the other hand, extensive local damage did not cause

**Table D-III**  
**FAILURES OBSERVED DURING TEST NO. 3 IN THREE-PLY LAMINATED BEAMS CONSTRUCTED WITH TWO ANNEALED PANES**

Specimen No. and Manufacturer	Specimen Description	Temperature °F	Description of Damage
3-A Glass Co.	13/64-in. annealed glass (2 plates) 1/8-in. plastic	- 76 -102	Slight edge cracks. Numerous small cracks along both long edges of one glass pane.
3-B Glass Co.	13/64-in. annealed glass (2 plates) 1/8-in. plastic	-112	No cracks observed.
5 ARF	13/64-in. annealed glass (2 plates) 0.26-in. plastic	- 33 - 64 - 86	Fracture during Test No. 1. Additional fracture. Piece of glass separates from laminate.
6 ARF	13/64-in. annealed glass (2 plates) 0.12-in. plastic	- 76 -102 -112	Slight edge cracks near one spot. Indications of fractures at two corners at same edge. Development of some cracks on short edge. Fracture extended from one corner. Transverse crack on opposite side.
7 ARF	13/64-in. annealed glass (2 plates) 0.020-in. plastic	- 76 -102 -112	Single longitudinal crack on one face. Single transverse crack on opposite face near center, 3 hours after standing. Second transverse crack opposite face.
4-A Glass Co.	13/64-in. annealed glass, 3/8-in. annealed glass, 1/8-in. plastic	- 76 -102 -112	Three slight edge cracks along long edge after standing. Small areas of edge chipping on one edge of 3/8-in. glass. Edge cracks on 3/8-in. glass after standing 24 hours.
4-B Glass Co.	13/64-in. annealed glass, 3/8-in. annealed glass, 1/8-in. plastic	-112	No cracks observed.

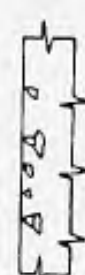


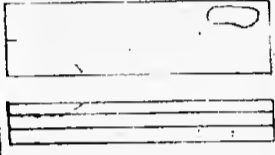
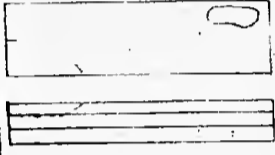
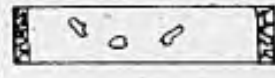
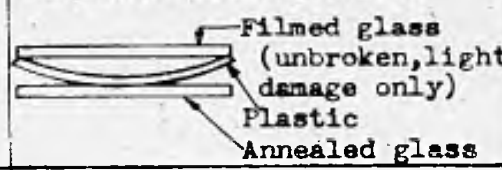

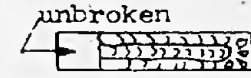
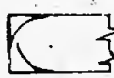



Table D-IV

FAILURES OBSERVED DURING TEST NO. 3 IN THREE-PLY LAMINATED BEAMS CONSTRUCTED WITH ANNEALED AND FULLY TEMPERED PANES

Specimen No. and Manufacturer	Specimen Description	Temperature of	Description of Damage	Fracture Surface No. 1 (Tempered Glass)	Fracture Surface No. 2 (Annealed or Tempered)
12-A Glass Co.	13/64-in. fully tempered glass, 13/64-in. annealed glass, 1/8-in. plastic	-102	Fracture visible along long edge. No trace of fracture origin at edge. Fracture seems internal.		Single edge chipping damage (see Fig. E-6b).
		-112	Cracks and chipping on one side. No separation of annealed glass.		
12-B Glass Co.	13/64-in. fully tempered glass, 13/64-in. annealed glass, 1/8-in. plastic	-112	No cracks noted after test.		Fragmentation of glass pane.
13-A Glass Co.	3/8-in. fully tempered glass, 1/4-in. annealed glass, 1/8-in. plastic	-76	Complete fragmentation of one side. Chipping failure on opposite side. Plastic bent away from chipped side.		Chipping failure - 1/2 length of beam (type 6b). See Fig. E-13.
		-102	Slight edge cracks at one spot (annealed glass). Crack at top corner of annealed glass.		Edge chipping of tempered pane.
		-112	Fracture at one corner. Evidence of chipping on one long edge and one short edge.		Deep fractures (see Fig. E-7).
13-B Glass Co.	3/8-in. fully tempered glass, 1/4-in. annealed glass, 1/8-in. plastic	-112	No evidence of failure.		
17 ARF	Thermocouple specimen 3/8-in. fully tempered glass (2 plates), 3/8-in. plastic	-76	Indications of edge chipping at several spots along long edge.		Complete fragmentation of glass pane. Much of remaining surface of plastic free of chips.
		-102	After this stand up, small areas of edge chipping at numerous points along long edges of both panes and at one spot on short edge.		Complete fragmentation of glass at interface. Chipping failure parallel to and close to interface (type 6b) apparently typical of tempered glass.
		-112	Complete fragmentation of both sides and transverse fracture of plastic.		

**Table D-V**  
**FAILURES OBSERVED DURING TEST NO. 3 IN THREE-PLY LAMINATED BEAMS**  
**CONSTRUCTED WITH ANNEALED, FULLY TEMPERED, AND FILMED GLASS**

Specimen No. and Manufacturer	History of Specimen	Specimen Description	Temperature °F	Description of Damage	Fracture Surface No. 1 (Filmed Glass)	Fracture Surface No. 2
8-A Glass Co.	Inserted at -80° F	13/64-in. filmed glass, 13/64-in. annealed glass, 1/8-in. plastic	- 76	White marks on filmed side. Slight edge cracks along long edge of annealed glass. Traces of delamination at one spot after standing over night.	Filmed glass pane undamaged except for chipping at a few spots and under bus bars.  See Fig. 10 	Coarse chipping (type 6a) parallel and close to surface near interface of annealed pane.
			- 86	Complete disintegration. 		
8-B Glass Co.	Carried through test	13/64-in. filmed glass, 13/64-in. annealed glass, 1/8-in. plastic	-102	Filmed pane complete fragmented. Chipping failure and single fracture of annealed plate. Plastic core bent as specimen 8-A.	Fragmented surface.	Coarse chipping (type 6a) parallel and close to surface near interface of annealed pane.
9 Glass Co.	Carried through test	13/64-in. filmed glass, 3/8-in. annealed glass, 1/8-in. plastic	- 86	Chipping failure of annealed glass. Fragmentation of filmed glass. 	Fragmented surface loose; fragments with a few chips, mostly smooth polished surface.	Coarse chipping (type 6a) of annealed pane (see Fig. E-11).
10-A Glass Co.	Inserted at -80°	13/64-in. filmed glass, 13/64-in. fully tempered glass, 1/8-in. plastic	- 76	White marks on coated surface. Chipping at one spot after standing over night.	Chipping failure (type 6b) - 2/3 of length of pane. Bond failure at edge. 	Fine chipping (type 6a) typical of tempered glass parallel and close to interface of fully tempered pane.
			- 86	Complete fragmentation of top pane 2/3 length. Some chipping of tempered glass. Plastic core and broken filmed glass bent as above.		
10-B Glass Co.	Carried through test	13/64-in. filmed glass, 13/64-in. fully tempered glass, 1/8-in. plastic	-102	Light areas on filmed side (perhaps film failure).	Fragmentation failure. Many loose fragments. Some small chips attached to plastic.	Fine chipping (type 6a) typical of tempered glass parallel and close to interface of fully tempered pane.
			-112	Complete fragmentation of filmed glass. Plastic separated by chipping and bent away from tempered glass.		
11-B Glass Co.	Carried through test	13/64-in. filmed glass, 3/8-in. fully tempered glass, 1/8-in. plastic	-102	Light areas (perhaps film failure).	Fragmentation failure. Many loose fragments. A few fragments and small chips attached to plastic.	Fine chipping (type 6a) typical of tempered glass parallel and close to interface of fully tempered pane.
			-112	Complete fragmentation of filmed glass. Plastic separated by chipping from tempered glass. Plastic core fragments of filmed glass bent same as specimen No. 9.		
11-A Glass Co.	Inserted at -112° F	13/64-in. filmed glass, 3/8-in. fully tempered glass, 1/8-in. plastic	-112	Complete fragmentation of filmed glass. Plastic separated by chipping from tempered glass. Plastic core fragments of filmed glass bent same as specimen No. 9.	Fragmentation failure. Many loose fragments and small chips attached to plastic.	Fine chipping (type 6a) typical of tempered glass parallel and close to interface of fully tempered pane.
14 ARF		13/64-in. filmed glass (2 plates), 13/64-in. plastic	- 22	Edge chipped off. 	Chipping failure (type 6b) 2/3 of length of filmed glass. Bond failure at edge.  unbroken glass chips 	Same as lamina on opposite side.
			- 76	Fragmentation of one side. Indications of chipping opposite pane after standing over-night.		
16 ARF		13/64-in. filmed glass (2 plates), 13/64-in. plastic	- 76	Fragmentation 2/3 length of one side. Failure by chipping 1/2 length on other side. Plastic fragments of filmed glass bent same as specimen No. 9.	Chipping failure (type 6b) 2/3 of length of filmed glass. Bond failure at edge.	Chipping failure (type 6a) 2/3 of length. See Fig. E-13.

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failure in many beams during quenching tests under the most severe conditions. In many instances, damage appeared a considerable time after conclusion of the test; in others, cracks which originated during the test grew after its conclusion. Local damage, therefore, does not usually lead to destructive failure, and may occur as an alternative to destructive failure.

#### B. Types of Damage and Failure Observed

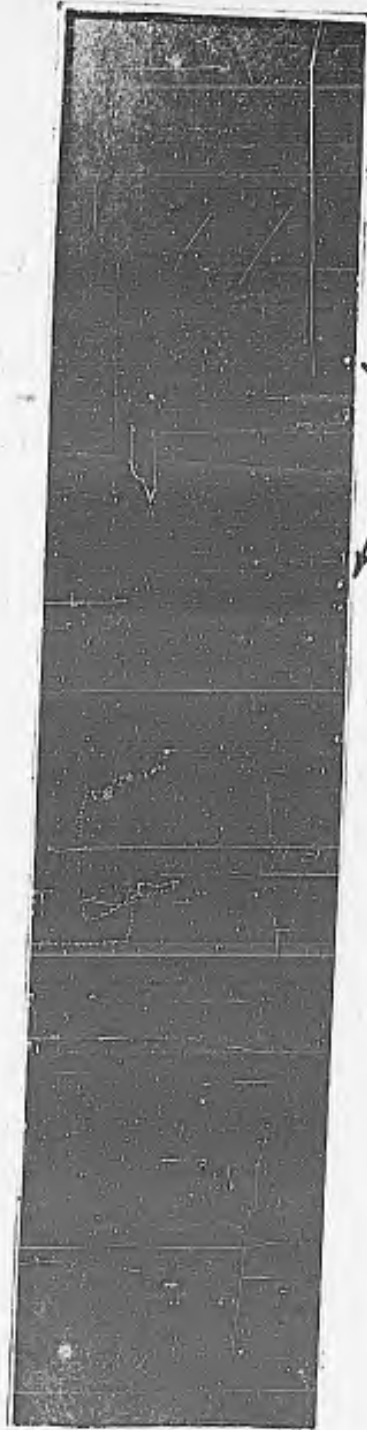
While nearly all failures in two-ply beams followed the same pattern, different types of failure were observed in three-ply beams. The types of failure observed are illustrated in Figs. D-5 through D-14, and are discussed below.

##### 1. Type 1 Failure: Edge Cracks

An example of edge cracks is shown in Fig. D-5 (specimen No. 3). These cracks developed at the edge near the interface during the test. Most of the cracks originated on the beveled portion of the edge of the glass specimen. Edge cracks of this nature represented the smallest amount of damage observed in any of the beams. A multitude of edge cracks was observed in all beams which had sharp (not beveled) edges.

##### 2. Type 2 Failure: Edge Chipping

Examples of edge chipping in annealed and tempered glass are shown in Figs. D-6a and D-6b, respectively. Small conchoidal fractures developed at the edges near the interface.



Edge Cracks

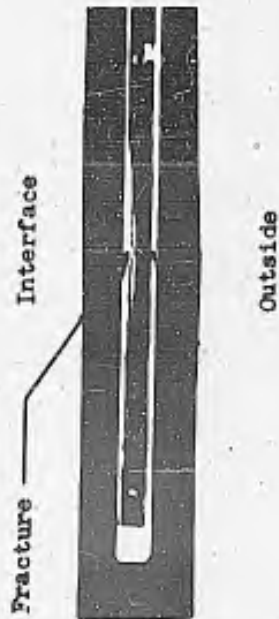
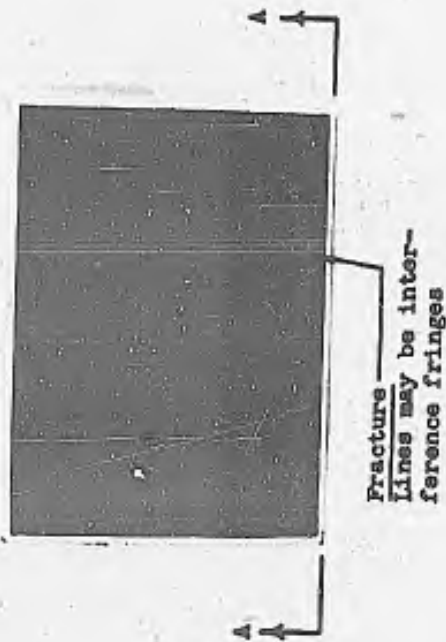
FIG. D-5 EDGE CRACKS IN ANNEALED GLASS -- TYPE 1 FAILURE (SPECIMEN NO. 3, TEST NO. 1)



Fig. D-6a EDGE CHIPPING IN ANNEALED GLASS -- TYPE 2 FAILURE (SPECIMEN NO. 4, TEST NO. 3)



FIG. D-6b EDGE CHIPPING IN TEMPERED GLASS -- TYPE 2 FAILURE (SPECIMEN NO. 10-A, TEST NO. 3)



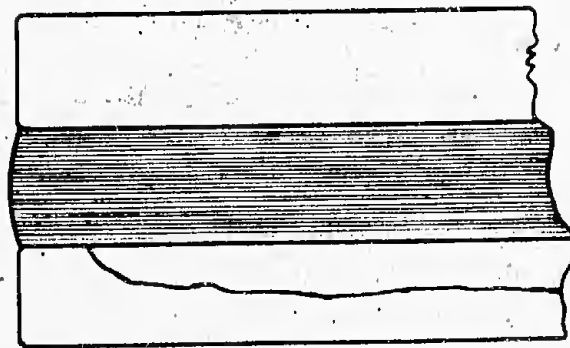
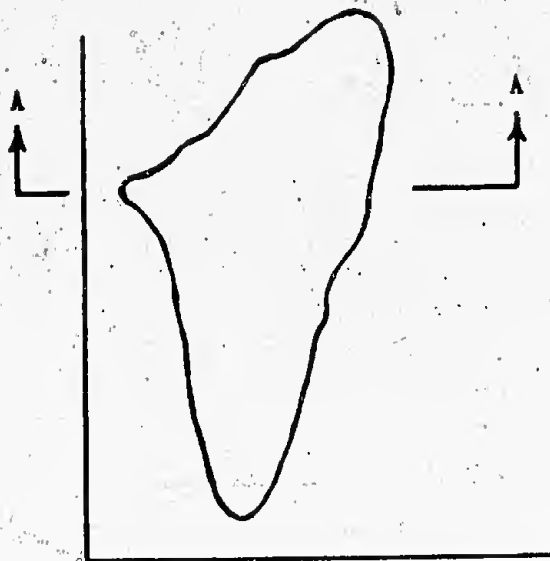
View AA

Photogram through Edge of Damage Glass Pane --  
Deep Fracture (Specimen No. 13-A, Test No. 3)



Edge Chipping  
Deep Fracture (Specimen No. 4,  
Test No. 3)

FIG. D-7 DEEP FRACTURE AND EDGE CHIPPING DAMAGE



Fracture Path

Section AA

Fig. D-8 DEEP FRACTURES IN ANNEALED GLASS --- TYPE 3 FAILURE

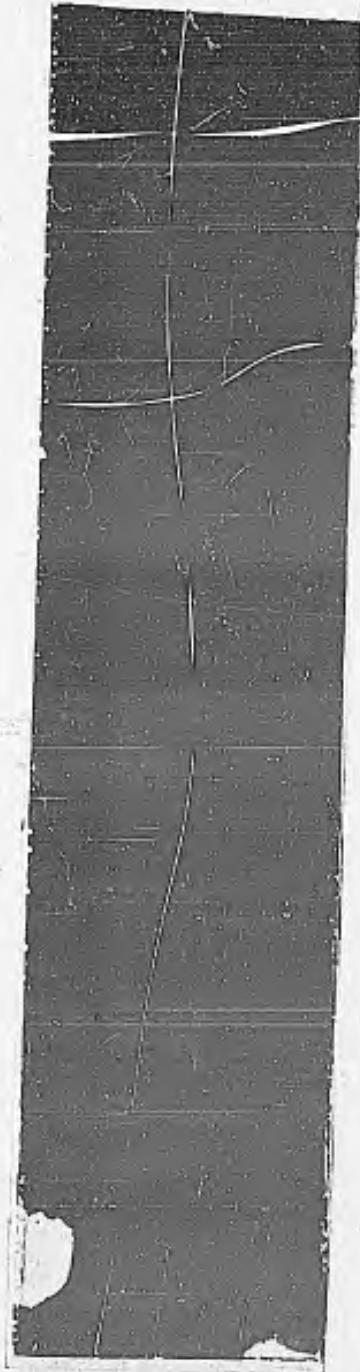


Fig. D-9 TRANSVERSE FRACTURES IN ANNEALED GLASS -- TYPE 4 FAILURE  
(SPECIMEN NO. 7, TEST NO. 3)

Note Extensive Edge Cracks



Chipping of Glass at Interface

Edge Chipping

Damaged Spot of Conductive Coating

Photogram of Filmed Glass Pane (Specimen No. 8, Test No. 3). The Coated Surface of Glass at the Interface. Note Extensive Chipping under Bus Bars at the Left End of the Pane.



Glass Chips Remaining on Plastic

Westinghouse Sensing Element

Photogram of Plastic Interlayer (Specimen No. 11, Test No. 3). Surface of Plastic Near Conductive Coating.

FIG. D-10 FAILURE AT THE INTERFACE THROUGH THE BOND -- TYPE 5 FAILURE



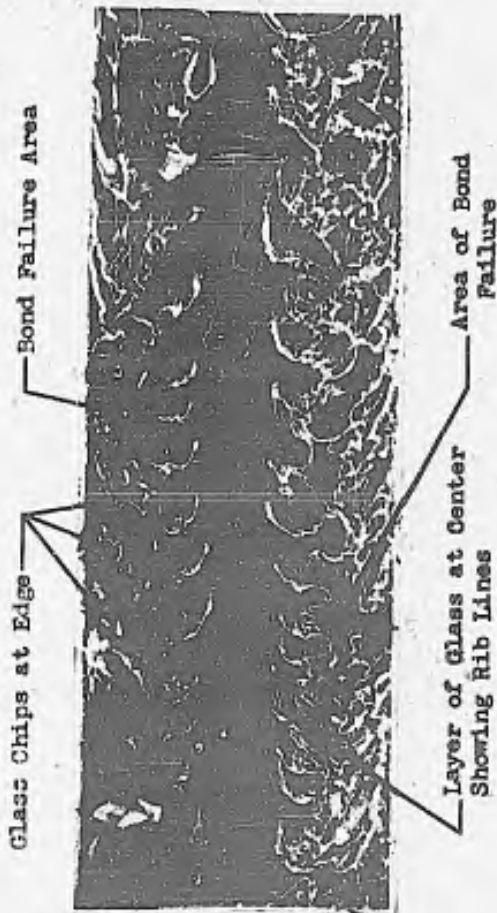
FIG. D-11 CHIPPING FAILURE IN ANNEALED GLASS -- TYPE 6A FAILURE  
(SPECIMEN NO. 9, TEST NO. 3)



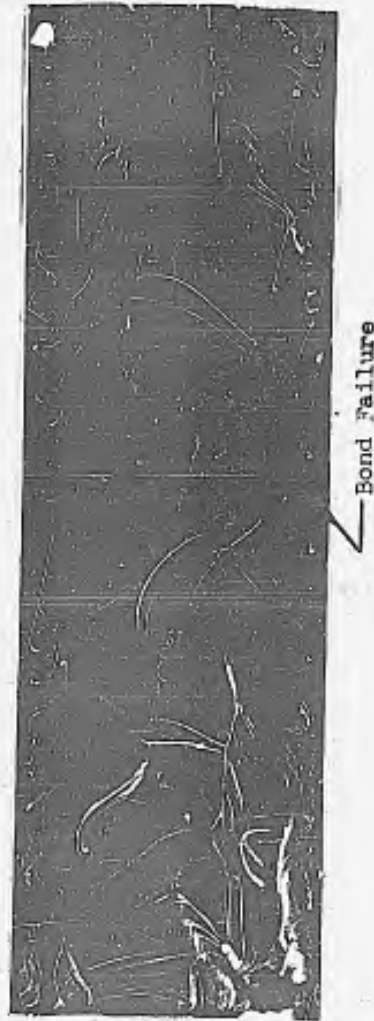
Fig. D-12 CHIPPING FAILURE IN FULLY TEMPERED GLASS—TYPE 6A FAILURE  
(SPECIMEN NO. 10, TEST NO. 3)

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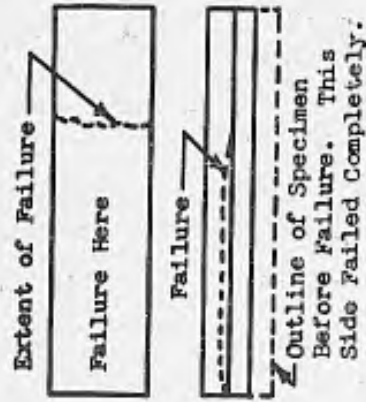
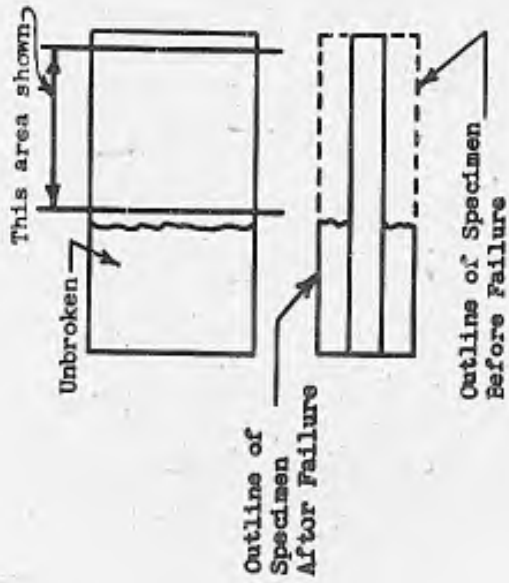
Photomicrograph of Surface of Plastic Interlayer (Specimen No. 16, Test No. 3) Interface Near Filmed Surface Shown.



Photomicrograph of Tempered Glass Pane (Specimen No. 15, Test No. 3)

FIG. D-13 FAILURE THROUGH GLASS PARALLEL AND CLOSE TO INTERFACE -- TYPE 6B FAILURE

Chipping Failure. Fracture Path Longitudinal.



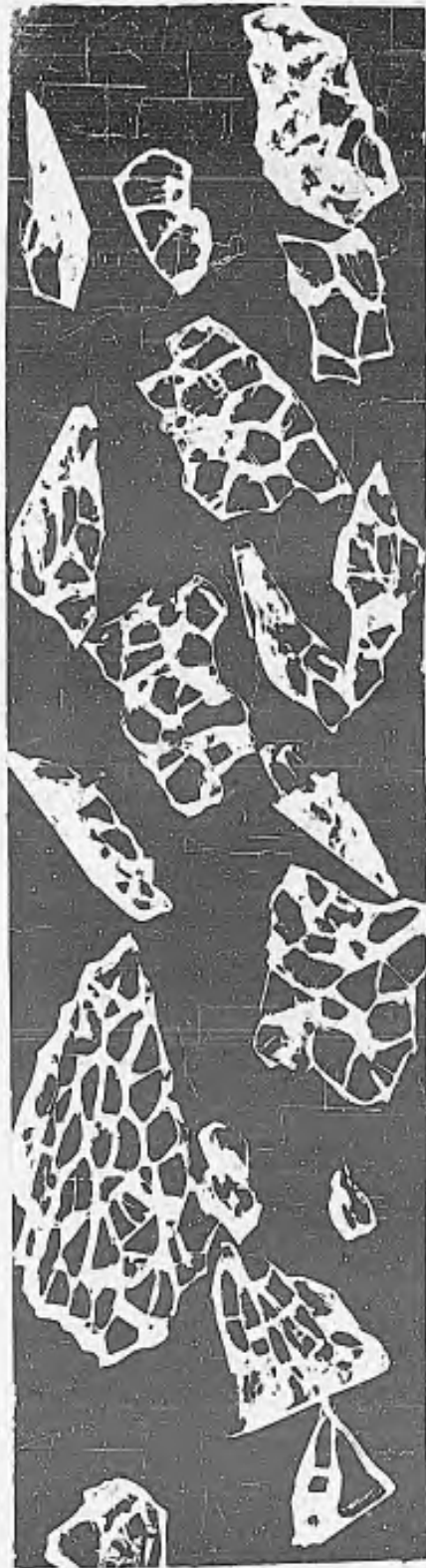


FIG. D-14 GLASS FRAGMENTS — SHATTERING OF TEMPERED GLASS — TYPE 7 FAILURE

(SPECIMEN NO. 17, TEST NO. 3)

3. Type 3 Failure: Deep Cracks

An example of deep crack failure is shown in Fig. E-7. These cracks, which were observed only in annealed glass, started from the interface and penetrated into the pane. A schematic drawing of this failure, which had a smooth surface, is shown in Fig. D-8. A view perpendicular to the fracture surface is shown in Fig. D-7.

4. Type 4 Failure: Transverse Cracks

Figure D-9 shows the only such fracture observed in the course of these tests. This failure, which occurred in specimen No. 7, consisted of a longitudinal crack on one side of the beam and two transverse cracks in the opposite pane.

5. Type 5 Failure: Failure at the Interface through the Bond (Delamination)

In many cases, part or nearly all of the failure consisted of separation of glass and plastic at the interface, as illustrated in Fig. D-10. Specimen No. 8 shows an extreme case in which nearly the entire failure was delamination. Only a few chips were pulled from the glass. Specimen No. 11 shows the interface surface of the plastic after the glass pane located next to this interface had shattered, much of the debris falling off the plastic after fracture. Only a few chips of glass remained attached to the plastic.

6. Type 6 Failure: Failure through the Glass Parallel and Close to the Interface (Chipping Type Failure)

Examples of a chipping type failure are shown in Figs. D-11, D-12, and D-13. This type of failure was observed in two-ply beams, and also in many three-ply beams during Test No. 3. The texture observed in fractures of annealed glass was generally much coarser than that of tempered glass. Fracture surfaces of annealed and tempered panes, both from three-ply beams, are shown in Figs. D-11 and D-12, respectively. These figures show fractures which traveled from the long edges inward in a regular pattern. This is called type 6a failure.

In several three-ply beams, a chipping type fracture showed a less orderly progress of the fracture front, as shown by the irregular pattern of rib lines and hackle marks in Fig. D-13 (specimens No. 15 and 16). In both instances, most of the fracture seems to have traveled the length of the beam; also, it is likely that bond failure took place near the long edges of the laminate. This is called type 6b failure.

7. Type 7 Failure: Shattering of Tempered Glass

Shattering of tempered and filmed glass panes was observed in many beams. Fracture of these beams was caused by a system of cracks perpendicular to the face of the pane. Figure D-11 (specimen No. 17) shows the glass fragments remaining from such a failure.

C. Effect of Alcohol Attack on the Exposed Edges of the Plastic

During the course of Test No. 3, it was noted that the repeated submersion of the beams in alcohol attacked the edges of the plastic core. To determine whether this edge corrosion had reduced the extent of damage

suffered by the beams, several specimens were duplicated and immersed in a  $-80^{\circ}$  F bath. Table D-VI shows the effect of edge corrosion of the plastic in three-ply beams prepared by the glass companies. No duplicate specimens were available for the beams laminated by ARF, all of which had developed considerable local damage during previous immersions.

None of the beams developed local damage at the edges after edge corrosion of the plastic core had taken place; however, all beams which entered the bath for the first time at  $-80^{\circ}$  F did develop damage.

Attack of the plastic by alcohol did not prevent the failure of beams constructed with a coated pane; however, there is evidence that the fracture was delayed by the attack of alcohol on the plastic. New specimens (No. 8-A and 10-A) failed at a higher temperature than their duplicates which had been carried through the test. No duplicates were available for the other specimens made with a conductive coating, except for specimen No. 11. Therefore, no valuable comparison was possible.

These tests indicate that corrosive attack on the exposed edge of the plastic affects the failure characteristics of three-ply laminated beams. In all instances, the development of damage was delayed or prevented, and in two instances, disintegration failure seems to have been delayed.

#### D. Comparison of Commercial Beams with Beams Laminated by ARF

Seven of the beams tested had been laminated in the ARF laboratory autoclave, while all others were fabricated by the glass companies. Beams laminated in the laboratory differed from the commercially prepared specimens in the following manner:

Table D-VI

EFFECT OF ALCOHOL CORROSION ON DAMAGE IN THREE-PLY BEAMS

Specimen No.	Specimen Description	For First Time Inserted at - 80° F in Test No. 3	Carried Through Tests No. 1, 2, and 3
3	13/64-in. annealed glass (2 plates), 1/8-in. plastic	- 80° F, slight edge cracks. - 100° F, slight edge cracks.	no cracks.
4	13/64-in. annealed glass, 3/8-in. annealed glass, 1/8-in. plastic	- 80° F, slight edge cracks after standing 24 hours. - 100° F, small areas of edge chipping on 3/8-in. glass.	no cracks.
12	13/64-in. fully tempered glass, 13/64-in. annealed glass, 1/8-in. plastic	- 100° F, deep fracture in glass. - 112° F, edge cracks, growth of deep fractures.	no cracks.
13	3/8-in. fully tempered glass, 1/4-in. annealed glass, 1/8-in. plastic	- 80° F, slight edge cracks. - 100° F, deep fracture at one corner of glass. - 112° F, one corner broken off. Deep fracture opposite corner.	no cracks.
8	13/64-in. filmed glass, 13/64-in. annealed glass, 1/8-in. plastic	- 80° F, white marks on filmed side. Slight edge cracks on long edge. Traces of edge chipping at one spot. - 90° F, disintegration failure.	- 100° F, disintegration failure.
9	13/64-in. filmed glass, 3/8-in. annealed glass, 1/8-in. plastic	no duplicate.	- 90° F, fragmentation of filmed pane, chipping of annealed glass.
10	13/64-in. filmed glass, 13/64-in. fully tempered glass, 1/8-in. plastic	- 80° F, white marks on filmed surface. Edge chipping at one spot. - 90° F, complete fragmentation of filmed glass 2/3 length. Some chipping of tempered glass.	- 100° F, white marks on filmed side. - 112° F, complete fragmentation of filmed pane. Chipping of tempered glass.
11	13/64-in. filmed glass, 3/8-in. fully tempered glass, 1/8-in. plastic	no valuable duplicate.	- 100° F, white marks on filmed surface. - 112° F, disintegration failure.

1. Since ARF had comparatively little experience in the lamination of glass and plastic, it is likely that the bond produced in ARF laminated beams was inferior to that of commercially laminated beams.

2. While the edges of the glass panes used in commercial beams were beveled, the edges of the plates used in the laboratory-laminated specimens were straight (see Fig. D-15). The edges of the square-cut glass panes contained a few visible cracks and possibly many microscopic cracks.

The effect of straight edges may be described as follows:

(1) stresses at the square edge differ from stresses at the beveled edge, and (2) cracks already existing at the square edge are points of stress concentrations and, consequently, will grow under comparatively low applied stresses.

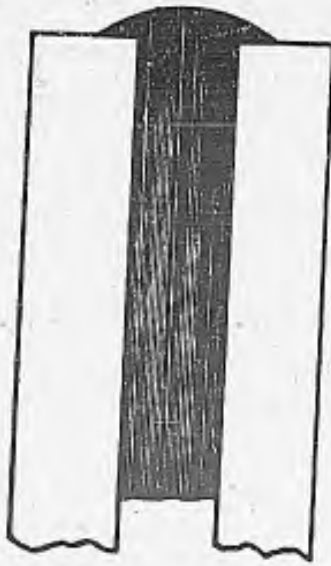
In general, beams laminated by ARF developed considerably more local edge cracks and other damage than the commercially prepared beams. Also, failures of ARF laminated beams generally occurred at higher temperatures than those of commercial beams where comparable samples were tested.

E. Comparison of Damage Suffered by Different Three-Ply Beams

The various beams tested are compared in Tables D-III, D-IV, and D-V.

1. Beams made with Two Laminae of Annealed Glass

Specimens No. 3, 4, 5, 6, and 7 were constructed with two panes of annealed glass. Specimens No. 3 and 4 were prepared commercially



Beam Laminated at ARF



Beam Supplied by  
Glass Companies

FIG. D-15 EDGES OF GLASS COMPANIES' AND ARF BEAMS

with a 1/8-in. plastic interlayer, No. 3 being symmetrical and No. 4 asymmetrical. Specimens No. 5, 6, and 7 (symmetrical) were laminated in the ARF laboratory autoclave, the thicknesses of the plastic interlayers being 0.26, 0.12, and 0.02 in., respectively.

Comparison of specimens No. 3 and 4 may offer an indication regarding the effect of asymmetrical beam construction, while comparison of specimens No. 5, 6, and 7 may assist in determining the effect of interlayer thickness. Comparison of specimens No. 3 and 6 may serve as a means of evaluating commercial beams with those laminated by ARF.

The damage suffered by specimens No. 3 and 4 was of the same type, with slight local damage appearing along the long edge of both, beginning at  $-80^{\circ}$  F. In the asymmetrical beam, damage in the form of edge chipping (type 2 failure) occurred in the thicker pane only. In the symmetrical beam, both panes were damaged locally in the same area. This damage was observed only in the specimens which were first inserted at  $-80^{\circ}$  F. No damage was observed in these beams where attack of the plastic by the alcohol had occurred after the specimens had been carried through the entire series of immersions.

Specimen No. 5 was the only specimen which failed during Test No. 1. The failure began at a corner and traveled in the direction of the length of the beam, parallel to the interface until about two-thirds of the pane had broken off. The texture of the fracture was extremely coarse. A large area of the corner where the fracture originated showed bond failure (delamination). It is possible that bonding did not take place at this corner during the laminating process, thus causing failure at a much higher temperature than would be expected.

Both specimens No. 6 and No. 7 developed profuse edge cracks and small areas of edge chipping. Numerous edge cracks are typical of ARF laminated specimens, probably because these beams had square edges. Specimen No. 6 developed two deep fractures near two opposite corners (type 3 failure). These fractures were similar to deep fractures observed in the annealed pane of beams composed of annealed and tempered glass. It is difficult to determine the point of origin of such fractures, but it appears that they do not originate close to the edge.

Specimen No. 7 developed transverse cracks perpendicular to the interface (type 4 failure), one longitudinal crack on one pane and two transverse cracks on the opposite pane. These fractures differ from the fractures of all other beams. The fact that the fracture was perpendicular to the interface suggests that tensile stresses acting parallel to the interface were responsible. This is contrary to the fact that all evidence indicated that stresses acting in a direction parallel to the interface are compressive and, hence, would not be expected to cause failure. A possible explanation of this fracture is that it was caused by stresses due to thermal gradients during the quench.

2. Beams Made with One Lamina of Annealed Glass and One of Tempered Glass, and Beams Made with Two Laminae of Tempered Glass

The specimens considered in this section are listed in Table D-IV. Commercially laminated specimens No. 12 (symmetrical) and No. 13 (asymmetrical) contained an annealed pane and a fully tempered pane; specimens No. 15 and 17 (symmetrical) were each composed of two tempered panes; specimen No. 15 was constructed of 13/64-in. glass panes with a

13/64-in. thick plastic core; and specimen No. 17 was made with 3/8-in. glass panes and a 3/8-in. plastic core.

Specimens No. 12 and 13 revealed the result of combining tempered and annealed glass in one beam. Comparison between the two specimens shows the effect of asymmetrical beam construction.

Specimens No. 12-B and 13-B, which were carried through the test, suffered no damage, whereas the duplicate specimens which were first inserted at  $-80^{\circ}$  F were damaged locally. Specimen No. 12-A developed two deep fractures at  $-100^{\circ}$  F in the annealed glass pane near the long edge, and showed a number of edge cracks and edge chipping at  $-112^{\circ}$  F. Edge chipping in the tempered pane opposite the damaged area in the annealed pane was also observed. Specimen No. 13-A developed a deep fracture (type 3 failure) in the annealed pane near one corner at  $-102^{\circ}$  F (see Fig. D-7). At  $-112^{\circ}$  F, the opposite corner broke off, probably due to a similar fracture, and considerable edge chipping occurred in the tempered pane.

In both of these specimens most of the damage occurred in the annealed glass. The annealed pane of specimens No. 12-A and 13-A suffered more damage than either of the panes of similarly constructed specimens No. 3-A and 4-A, which were made entirely of annealed glass.

In specimen No. 15 one pane shattered completely, and chipping parallel to the interface (type 6b failure) occurred in the opposite pane. The appearance of the fracture surface indicates that most of the fracture traveled the length of the pane which was not shattered. At the conclusion of the test, the plastic appeared curled away from the unshattered pane.

Specimen No. 17 exhibited edge chipping and cracks at  $-80^{\circ}$  F. At  $-112^{\circ}$  F, both panes shattered and the plastic broke with a transverse fracture. This was the only instance in which damage to the plastic was observed.

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In general, beams constructed of one annealed and one tempered glass pane developed considerable local damage in the annealed pane, and some local damage in the tempered pane. Beams made of two tempered panes failed completely; the only beams of this type were laminated in the ARF laboratory.

3. Beams made with Laminae of Filmed Glass in Combination with Laminae of Filmed and Tempered Glass

Specimens No. 8, 9, 10, 11, 14, and 16 were constructed with either one or two filmed glass panes with the film located at the interface of glass and plastic. Specimens No. 8-A, 8-B, and 9 had an annealed pane opposite a filmed pane; No. 8 was symmetrical and No. 9 asymmetrical. Specimens No. 10-A, 10-B, 11-A, and 11-B had a fully tempered pane opposite a filmed pane; No. 10 was symmetrical and No. 11 was asymmetrical. Specimens No. 8, 9, 10, and 11 were supplied by the glass companies, whereas specimen No. 14 was laminated in the ARF laboratory; it was made of two filmed glass panes with the filmed surfaces at the interfaces. Specimen No. 16 was made of two filmed panes with one of the filmed surfaces at an interface and the other not at an interface; therefore, it was comparable to specimen No. 10, except for the fact that the filmed pane with the film facing out was not fully tempered.

These specimens introduce the effect of a conductive film on the resistance to failure of laminated beams. This condition actually exists in the airplane windshield. Since the filmed panes were partially tempered, all of the specimens contained at least one tempered pane.

All specimens containing a filmed pane (both commercially laminated specimens and those laminated in the ARF laboratory) were damaged in the course of the test. Specimens No. 8-B and 10-B failed at a lower temperature than specimens No. 8-A and 10-A, apparently due to the corrosive effect of

the alcohol on the plastic in former specimens, which tended to reduce stress concentrations along the edges. No comparison was possible for specimens No. 11-A and 11-B.

No local damage at the edges was observed at the filmed interface of specimens No. 8, 9, 10, 11, 14, and 16 prior to destructive failure. Small local damage (edge chipping) occurred at interfaces without film in the specimens where the plastic had not been exposed to attack by alcohol through a series of tests before destructive failure occurred.

The fracture of all specimens had certain features in common. In all specimens containing only one filmed pane, the plastic curled away from the other pane, together with a thin layer of glass pulled from the pane by a type 6 failure. The filmed pane shattered with the type of fracture which is typical of tempered glass. In one instance (specimen No. 8-A), the filmed pane was preserved almost without damage and only a few chips were pulled from the glass, except underneath the bus bars where chipping (type 6 failure) occurred. Chipping underneath the bus bars occurred in all beams in which failure at a filmed interface took place, the bus bars adhering to the plastic after separation of glass and plastic.

Inspection of the interface of the plastic which had been in contact with the filmed glass surface in specimens No. 8-A, 8-B, 9, 10-B, 11-A, and 11-B (made by the glass companies) revealed that most of the separation of glass and plastic at this interface had been a bond failure so that only small chips of glass were left on the free interface. In most instances, damage to the conductive film was observed. Resistance measurements showed that in all beams most of the conductive film remained attached to the glass, except for the bus bars which remained with the plastic.

The commercial specimen No. 10-A and the ARF-laminated specimens No. 14 and 16 did not show extensive bond failure. Instead, delamination took place only at the edges, while most of the plastic interface after failure was covered by a thin layer of glass pulled from the coated pane by a chipping type failure (type 6b failure). The fracture path was in the direction of the length of the beam, as shown by the texture of the fracture surface. Only a part of the pane broke off, the remainder staying attached to the plastic interlayer.

In specimen No. 10-A, a chipping failure (type 6a) occurred over the entire length of the beam at the tempered glass-plastic interface. In specimen No. 14, two adjacent outside corners broke off at  $-22^{\circ}$  F. Both filmed panes separated from the plastic interlayer by a type 6b failure, as described above. In specimen No. 16, failure at the filmed interface occurred over part of the length of the beam, as described above. Failure at the other interface was of the usual chipping type (type 6a failure), but over part of the length of the beam only. These failures were similar to the failure of specimen No. 15, which was constructed of two tempered panes.

Failure of the specimens constructed with a tempered pane opposite the filmed pane generally occurred at a lower temperature than failure of the specimens where an annealed pane was located opposite the filmed pane. Specimen No. 10-B failed at a lower temperature than specimen No. 8-B; specimen No. 11-B failed at a lower temperature than specimen No. 9; and specimen No. 10-A failed at the same temperature as specimen No. 8-A.

The effect of asymmetry remains uncertain. Specimen No. 8-A (symmetrical) failed at a higher temperature than specimen No. 9 (asymmetrical). Specimen No. 10-B (symmetrical) failed at the same temperature as specimen No. 11-B (asymmetrical).

Local damage which was suffered by the filmed beams before failure was similar to that which occurred in beams made of two annealed panes. The damage occurred only at the interface at which no film was present. The destructive failure of some of the filmed beams was similar to the failure of a beam made of two fully tempered panes (specimen No. 15).

In four specimens containing a filmed pane, small discolored spots in the interior of the beam were observed before fracture occurred (see Table D-V). Similar spots were observed on the plastic interface after separation of glass and plastic, and were identified as areas of conductive film which were attached to the plastic.

The fact that all beams containing a filmed pane failed is certainly significant, in that it indicates that the conductive film itself may have been responsible for the failures. This contention is supported by the fact that most of the failures at the filmed interface were delaminations with little damage to the glass. The fracture surface opposite the filmed pane was similar to those observed in two-ply beams. After the failure, the plastic was curled away from the pane which had no film. If it is assumed that the film interface failed first, such a failure would leave, in effect, a two-ply beam construction consisting of the other pane and the plastic core. Following the example of two-ply beams, the remaining structure would bend with the plastic on the concave side of the glass and produce a failure such as occurred in two-ply beams. The shape of the plastic after the test suggested that such a failure had occurred.

## V. CONCLUSIONS

### A. Nature of Conclusions

A complete interpretation of the results of this experiment is not possible since very little information exists on laminate interface stresses induced by uniform temperature changes. The results of these tests are therefore essentially descriptive and indicative of trends. It is possible that additional, more extensive tests might offer a better explanation of the cause and mechanism of cold-soak failures, although efforts to date have been rather unsuccessful. A summary of the observations made in the course of these tests is given below.

### B. Summary of Test Results

1. Two-ply beams constructed with annealed glass failed under slow uniform temperature changes (Tests No. 1 and 2). Temperature wise, these failures appeared to be reproducible with a reasonable degree of certainty.
2. Two-ply beams made with filmed glass failed under slow uniform temperature changes, but the magnitudes of the temperature changes producing failure were too widely scattered to be evaluated.
3. The growth of failures in two-ply beams followed a regular pattern, beginning at points on an edge and growing into the interior of the beam.
4. With one exception, three-ply laminated beams did not suffer any damage under either slow or accelerated uniform temperature changes down to  $-100^{\circ}$  F (Tests No. 1 and 2). These beams did incur damage during quenching in cold alcohol (Test No. 3).

5. Beams made of two panes of annealed glass and beams utilizing one pane of annealed and one pane of tempered glass developed local damage only.
6. Various types of local damage observed have been described.
7. Annealed glass generally suffered more local damage than tempered glass.
8. In the course of these tests, beams made entirely of annealed glass generally suffered less damage than beams employing annealed glass on one side and tempered glass on the opposite; however, annealed glass was damaged more severely than tempered glass.
9. Beams laminated in the laboratory autoclave generally failed more readily and showed more extensive local damage than beams fabricated by the glass companies.
10. It was observed that alcohol attacked the exposed edges of the plastic core, reducing or preventing local damage in most of the commercially prepared beams.
11. For beams containing a filmed glass surface at only one interface, the unfilmed pane separated from the plastic interlayer by a failure through the pane parallel and close to the interface, while the filmed pane generally shattered into fragments. In one instance, the filmed pane separated at the interface with little damage to the glass. These observations suggest that failure of a beam originates in the vicinity of the film. Similar failures occurred in beams made of two tempered glass panes which had been laminated in the laboratory.

12. Damage to the conductive film was observed on several beams.
13. The bus bars of filmed beams generally remained attached to the plastic, causing chipping of the glass during their separation from it. The conductive coating remained with the glass.
14. The effect of the geometry of a glass-plastic-glass laminate on its resistance to cold-soak was not determined successfully.

C. Interpretation of Results

The differences between ARF-laminated and commercially supplied beams have already been described. These differences may well account for the dissimilarity in the behavior of the beams.

The very large number of edge failures obtained during the course of these tests may be the result of high stress concentrations occurring along the edges of the specimens; however, no quantitative verification appears possible at this time.

It would be desirable to know which type of stress is causing failure. All available evidence indicates that glass fails in tension. On this assumption, most fractures in the glass seem to have been caused by tensile stresses nearly normal to the interface. Whether bond failures occurred under shear stresses parallel to the interface or under tensile stresses normal to the interface, is not evident from the results.

The tests indicated that the conductive film affects the strength of the laminated beam under cold-soak conditions. Damage to the conductive film was observed in many of the test beams. Since all three-ply beams containing a conductive film failed, it is evident that the conductive film affects the strength of the beam. The fact that considerable delamination

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took place in two-ply beams containing filmed panes, while little delamination took place in two-ply beams with annealed panes, and the evidence of delamination in three-ply beams with filmed panes, indicates that the coating reduces the bond strength.

Independent tests by Boeing Airplane Co. generally produced chipping in the tempered inner pane which is unheated, and near the bus bars at the outer pane, while delamination was most prominent at the filmed interface. This agrees well with the results of the tests described in this appendix.

No disintegration failures of windshields under cold-soak conditions in service have been reported, so that the failures produced in the present tests appear to be unusual and may indicate that the test conditions unduly exaggerate service conditions.

#### VI. CONTRIBUTING PERSONNEL

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