DEVELOPMENT OF AIRCRAFT WINDSHIELDS TO RESIST IMPACT WITH BIRDS IN FLIGHT
PART II

INVESTIGATION OF WINDSHIELD MATERIALS AND METHODS OF WINDSHIELD MOUNTING

By

Pell Kangas and George L Pigman
Aircraft Development Division

Technical Development Report No 74

CIVIL AERONAUTICS ADMINISTRATION
TECHNICAL DEVELOPMENT
INDIANAPOLIS, INDIANA
February 1950

TABLE OF CONTENTS

TABLE INDEX

Manuscript Received, November 1947

This report has been presented before the following

Society of Automotive Engineers,
National Air Transport Engineering Meeting
Kansas City, Mo , December 3, 1947

DEVELOPMENT OF AIRCRAFT WINDSHIELDS TO RESIST IMPACT WITH BIRDS IN FLIGHT

Part II

INVESTIGATION OF WINDSHIELD MATERIALS AND METHODS OF WINDSHIELD MOUNTING

SUMMARY

Impact tests of windshield installations were carried out by means of a compressed-air catapult, which projects freshly killed bird carcasses at velocities equivalent to aircraft flight speeds as great as 450 mph

Impact tests of various windshield materials and types of panel construction were conducted with panels mounted in both a standard laboratory test frame and in actual cockpit structures submitted for test by various manufacturers and air line operators Two principal types of windshield installation were tested The flat double-pane warm air de-icing type windshield was initially the primary type considered With the introduction of electrically heated panels, incorporating a transparent electrical conducting film, the single-pane type was included in the tests

It is shown that the primary factor affecting impact strength of laminated windshield panels themselves is the thickness of the plastic interlayer The most important factor, concerning the installation of the panels in the cockpits, is the method of attachment to the air frame structure

The test results show that the most efficient type of windshield panel construction as concerns high impact strength is the laminated type with thick polyvinyl butyral plastic interlayer, with an extended flexible plastic edge incorporating a metal insert bolted to the frame structure A glass-plastic panel of this type with 0 125 in polyvinyl butyral plastic interlayer, with an angle of slope of 41° and plastic temperature of 80° F, resists penetration of a 4-lb carcass at velocities up to 280 mph when tested in the standard steel frame Similarly, a panel with 0 25-in polyvinyl butyral plastic interlayer resists penetration at velocities up to 440 mph Panels tested in aircraft cockpit structures give lower penetration velocity values because of general greater rigidity of the supporting structure and less uniform edge support

Further data are given in connection with windshield frame design, edge mounting problems, strength of side and other windows, optical and thermal characteristics of panels, splintering problems, effect of panel mounting angle, effect of location of impact, and other general design problems

INTRODUCTION

The general problem of frequency and hazards of collision of aircraft with birds in flight, with particular reference to damage of windshield areas, is presented separately in Part I of this report [1]

In this, Part II, are given the results of tests concerned with the development of impact resistant windshields, and basic information applicable to their design Part II is in the nature of a progress report, and will be followed in the future by additional reports

The tests covered in the present report were initiated in 1942 by the Civil Aeronautics Administration as part of a development program looking to the increasing of the impact resistance of aircraft windshields to provide protection against collision with birds in flight This program was started as a result of requests from various air carrier operators, and from regulatory bodies within the Administration, which arose as a result of airplane collisions with large birds which had occurred in the preceding several years

[1] Pell Kangas and George L Pigman, "Development of Aircraft Windshields to Resist Impact with Birds in Flight," Part I, Technical Development Report No 62, January 1949

Windshield testing in connection with this program was started in July, 1942, at the laboratories of the Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pennsylvania This work was carried out under direct Civil Aeronautics Administration supervision, but utilized Westinghouse personnel, facilities, and special test equipment developed for the CAA by the Westinghouse Company The work at East Pittsburgh was terminated in November 1943

In February 1945, construction of windshield test facilities was completed at the CAA Experimental Station, Indianapolis, Indiana, and the test program was resumed This program continued through 1945 and a portion of 1946 During the remainder of 1946 and in 1947, only limited tests other than for private manufacturers were conducted, and no appreciable progress was made in the general test program

The present report covers results and conclusions obtained in this investigation from the time test work was started in 1942 until the present time Some test results were published[2] in January 1945, and the present report reviews the data presented in this earlier publication The data presented in the present report are still incomplete in many respects, and it is planned to complete such data during the future course of the program

The purposes of the test program have been to secure practical and basic information for use in the design of impact resistant windshields, to aid windshield and aircraft manufacturers in the development and application of improved designs, and to coordinate knowledge of optical, de-icing, and other windshield characteristics with impact resistance to arrive at optimum design requirements

The authors wish to acknowledge with appreciation the cooperation of the following aircraft manufacturers, air lines, and glass and plastic manufacturers for providing windshield installations and associated materials, numerous ideas and useful suggestions, and permission for use in this report of data obtained from tests on actual cockpit structures

American Airlines
Beech Aircraft Corporation
Boeing Aircraft Company
Consolidated Vultee Aircraft Corporation
Curtiss-Wright Corporation, Airplane Division
Douglas Aircraft Company, Incorporated
E I du Pont de Nemours & Company, Plastics Division
The Glenn L Martin Company
Grumman Aircraft Engineering Company
Libbey-Owens-Ford Glass Company
Lockheed Aircraft Corporation
Pittsburgh Plate Glass Company
Rohm & Haas Company
United Air Lines

TEST EQUIPMENT AND METHOD OF TEST

Impact Tests

In the conduct of the windshield impact tests a compressed-air gun is used to project bird carcasses at the windshield panel This gun is shown in Fig 1 Gun barrels from three to eight inches inside diameter are used, so that bird carcasses from approximately 1 to 16 pounds weight may be projected at any predetermined velocity to a maximum of about 450 mph

The chickens and turkeys used in the tests are killed by electrocution just prior to the test, and are fitted into a light cloth bag for insertion in the gun Bird carcasses are used for the tests because of the extreme difficulty and the uncertainty involved in obtaining a substitute type of projectile which will possess elastic characteristics identical to a real carcass during high speed impact, and because bird carcasses have been found to provide reproducible test results

The electrocution process is utilized in preparing the carcass for test in order to retain its characteristics as nearly as possible to those of the living condition

After leaving the muzzle of the gun, the carcass breaks a set of fine steel wires, shown in Fig 2, which are placed across its path for velocity measuring purposes Two wires of the set are spaced with a 5-foot separation, and are connected to a galvanometer oscillograph which indicates the corresponding time interval Two other wires

[2] George L Pigman, "Impact-Resistant Windshield Construction," Aeronautical Engineering Review, Vol 4, No 1, January 1945

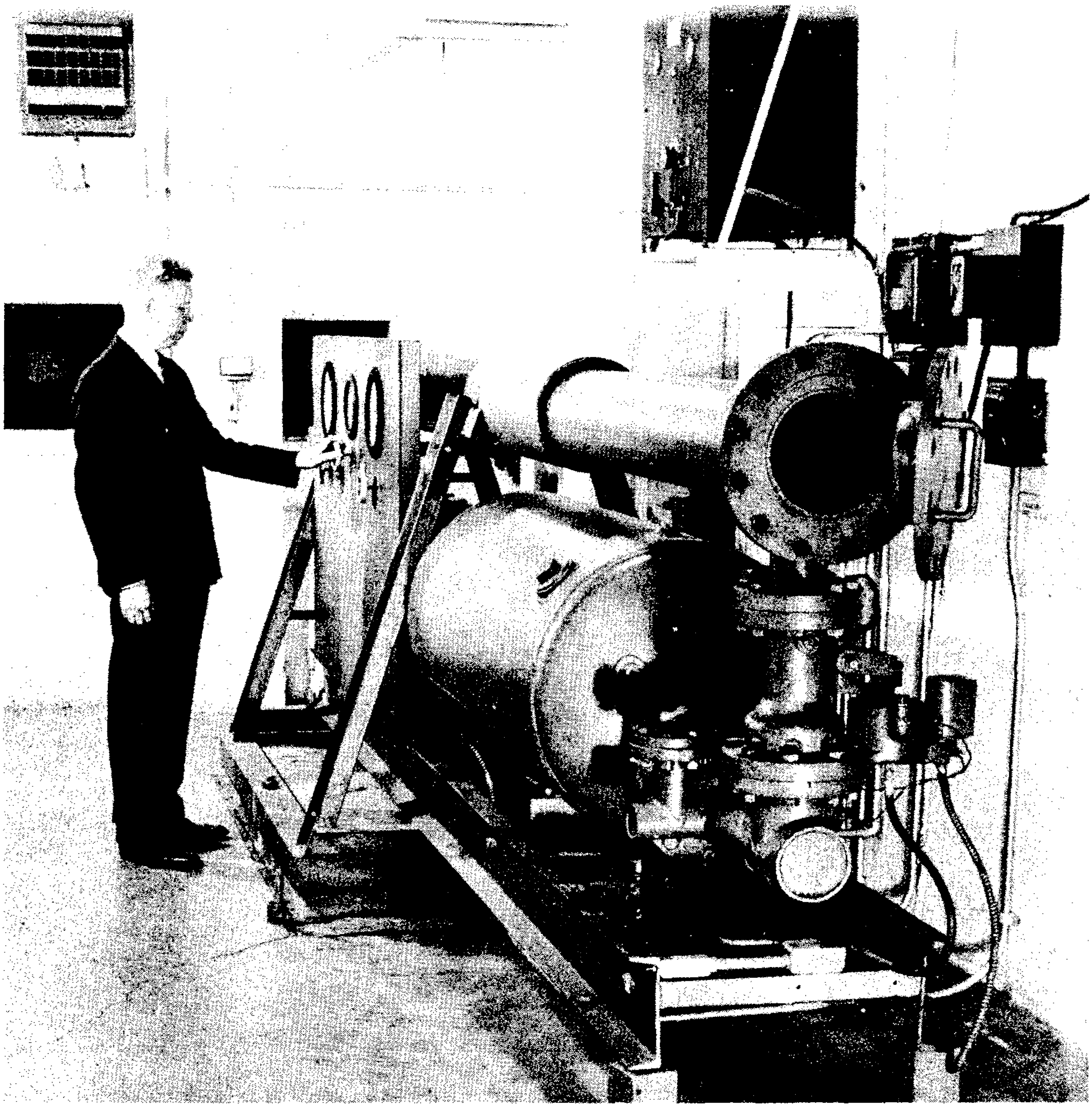


Fig. 1 Compressed Air Gun

of the set, also with a 5-foot separation, are connected to a direct-reading chronoscope. Thus two independent measurements of the carcass velocity are obtained. These instruments are in the control room shown in Fig. 3.

The carcass velocity obtained with the gun is predetermined in terms of the gun air-tank pressure, and may be predicted within approximately ±10 per cent. The point of impact of the carcass on the windshield structure is predetermined within about a 1-in. radius by bore-sighting the gun upon the point of the structure which is to receive the impact.

The windshield panels are mounted in various types of supporting structures for test. In most of the tests, in which the main purpose was to determine only the panel strength and panel impact characteristics

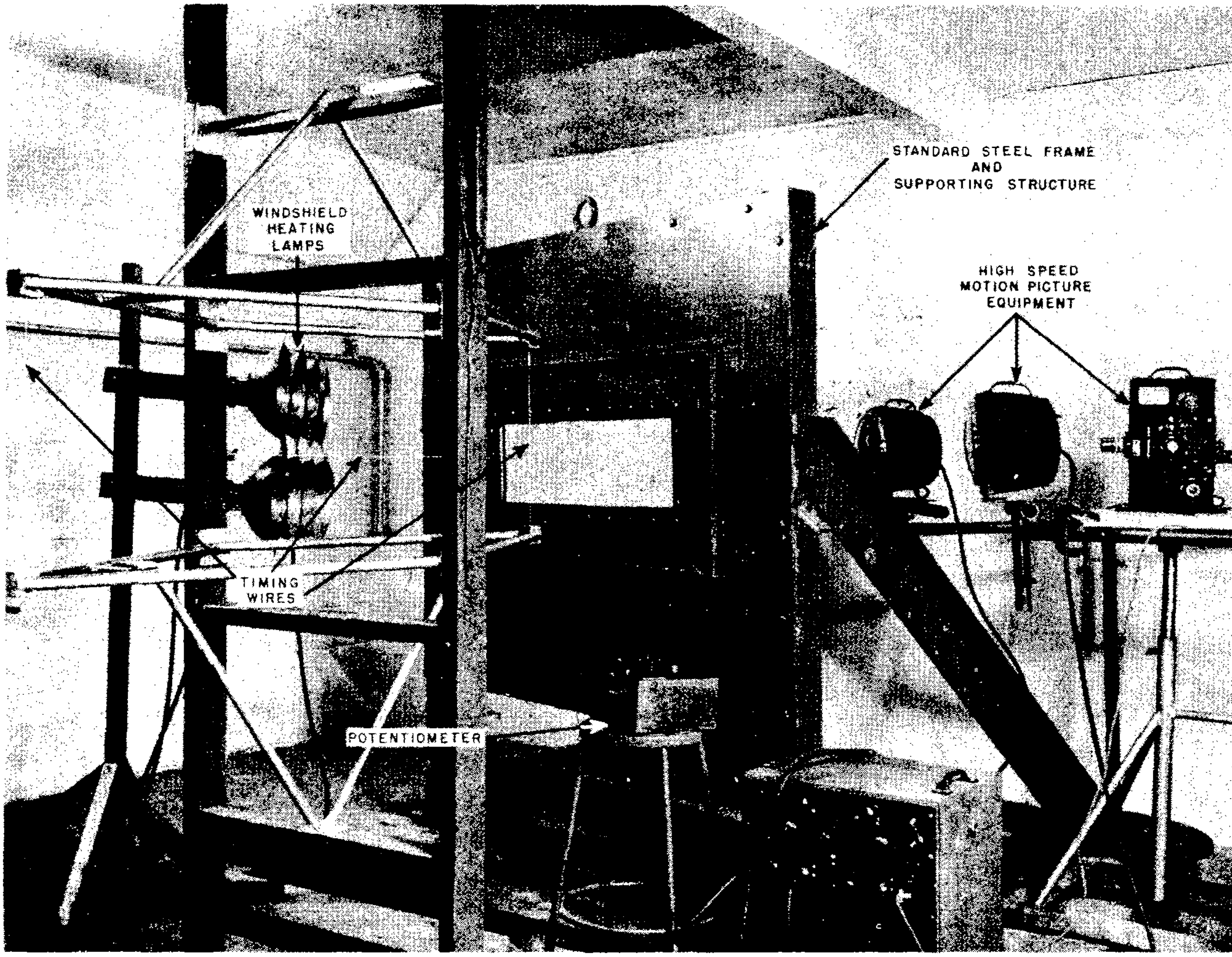


Fig. 2 Windshield Test Chamber

under various conditions, a standard steel frame structure was used. This structure, shown in Figs. 2 and 4, was adopted because of its simple construction and ease of repair, and was intended to have approximately the same elastic characteristics and rigidity as an average windshield frame structure on large aircraft. As will be shown later, this steel frame structure is actually less rigid, and apparently produced lower impact forces in the panel, than a normal cockpit structure of large aircraft.

Numerous tests have been carried out utilizing a portion of the airplane cockpit structure for mounting the test windshield panels. Tests of this nature have been conducted in cooperation with various aircraft manufacturers and air carrier operators, and have included the Douglas Models DC-4 and DC-6, Lockheed Model 49, Curtiss-Wright C-46-A and C-46-E, United Air Lines DC-3 and DC-4, Beechcraft Models D18S and 34, Martin Model 202, Boeing Model 377, Grumman G73, Consolidated Vultee Model 240, and others. In such tests the entire cockpit structure was used, including the structure above the approximate centerline of the fuselage and extending forward from the first bulkhead at the rear of the pilot compartment to a point several feet in front of the windshield. In Fig. 5 is shown a typical cockpit structure, in position for impact test in the test chamber. Fig. 5 also illustrates the method of support commonly used for such structures in the test chamber. The structure is clamped rigidly to the floor of the test chamber, and supported against the rigid rear wall by means of wood braces

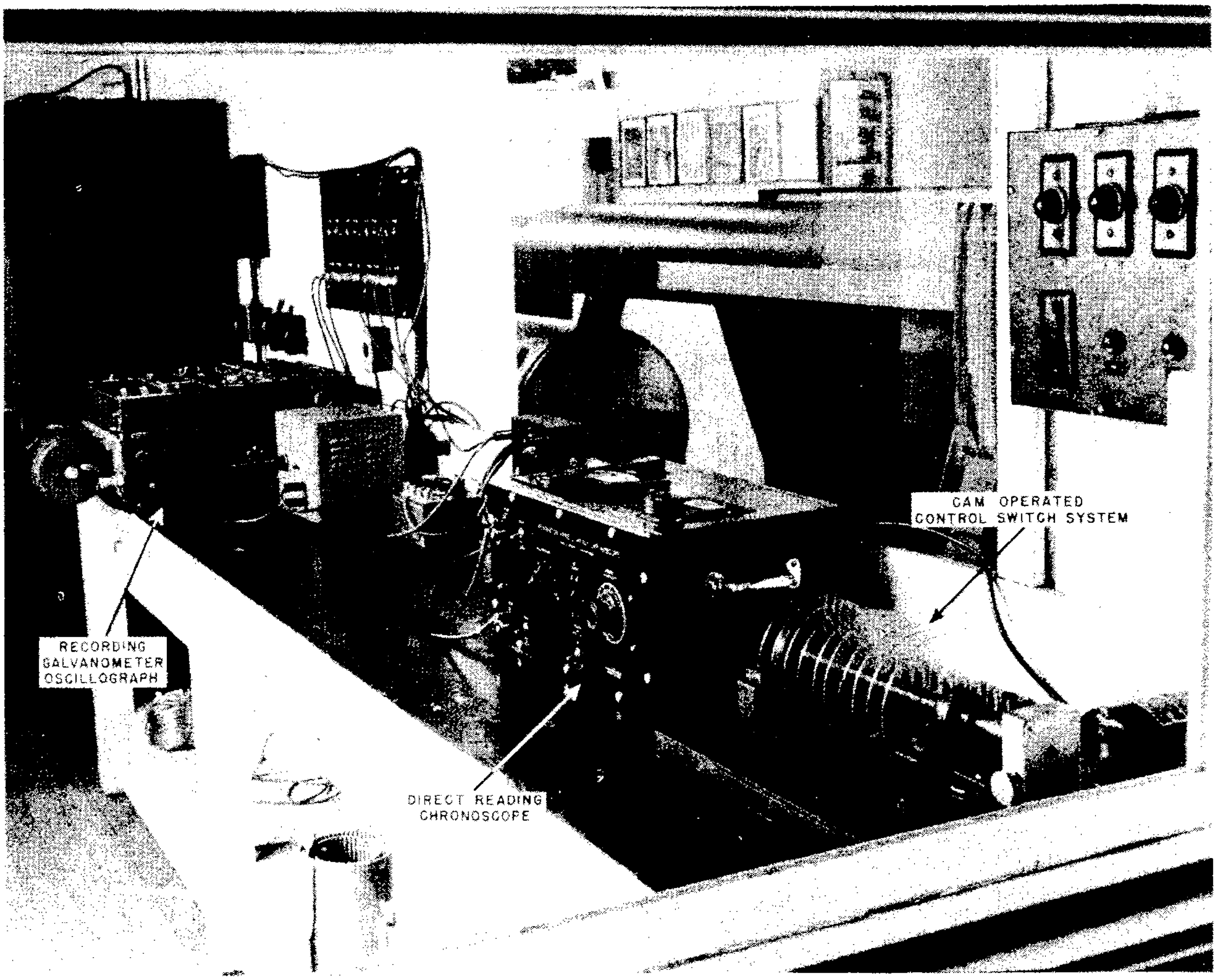


Fig. 3 Impact Test Control Room

behind each of the main longitudinal structural members.

Measurement of panel temperature at the time of test was obtained by thermocouples placed in close contact with each face of the panel. Panel heating to obtain desired temperatures was accomplished by means of heat lamps, and cooling was obtained by immersion of the panel in water of the desired temperature, or by cooling of the entire test chamber.

High-speed motion pictures were obtained of many of the windshield panels at the instant of impact as an aid in understanding the nature of the impact and the mechanism of the failures. For this purpose a General Radio Type 651-AG high-speed motion picture camera was used, and was operated at a speed of 1000-frames per second.

Optical Tests

Optical deviation tests of windshield panels were made by photographing a grid through the panel by means of a camera equipped with a long focal length lens, as shown in Fig. 6. The lens axis of the camera was placed perpendicular to both the plane of the panel and the plane of the grid. The distance between the windshield panel and the grid was arranged so that the 1-in. grid spacings corresponded to ten minutes of arc deviation of the line of sight.

A photograph of the grid was taken through the windshield panel, and then the panel was removed and a second photograph was taken of the grid upon the same photographic negative. Measurement of grid line displacements on an enlarged print of the

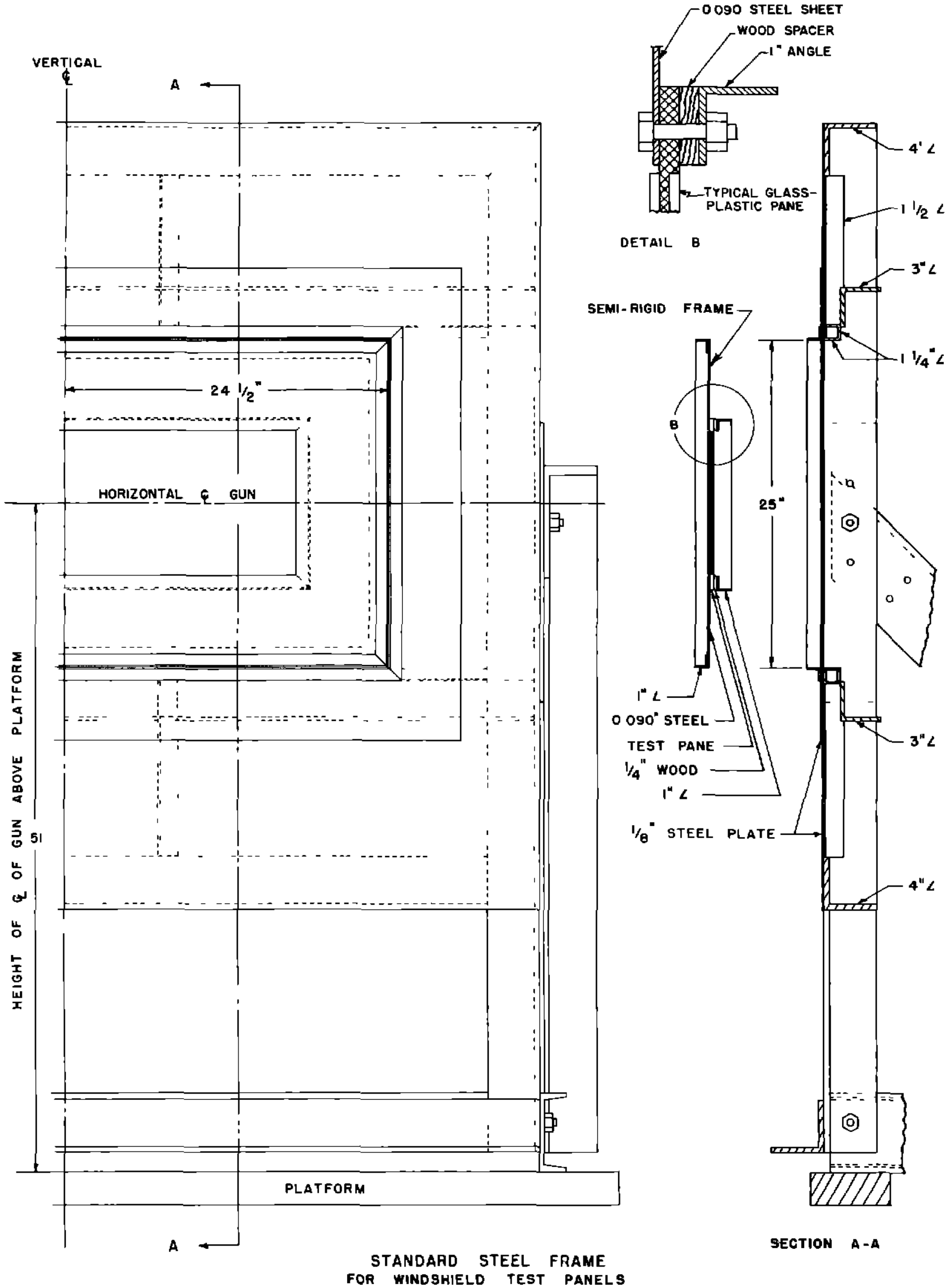


Fig 4 Standard Steel Frame and Supporting Structure For Windshield Test Panels

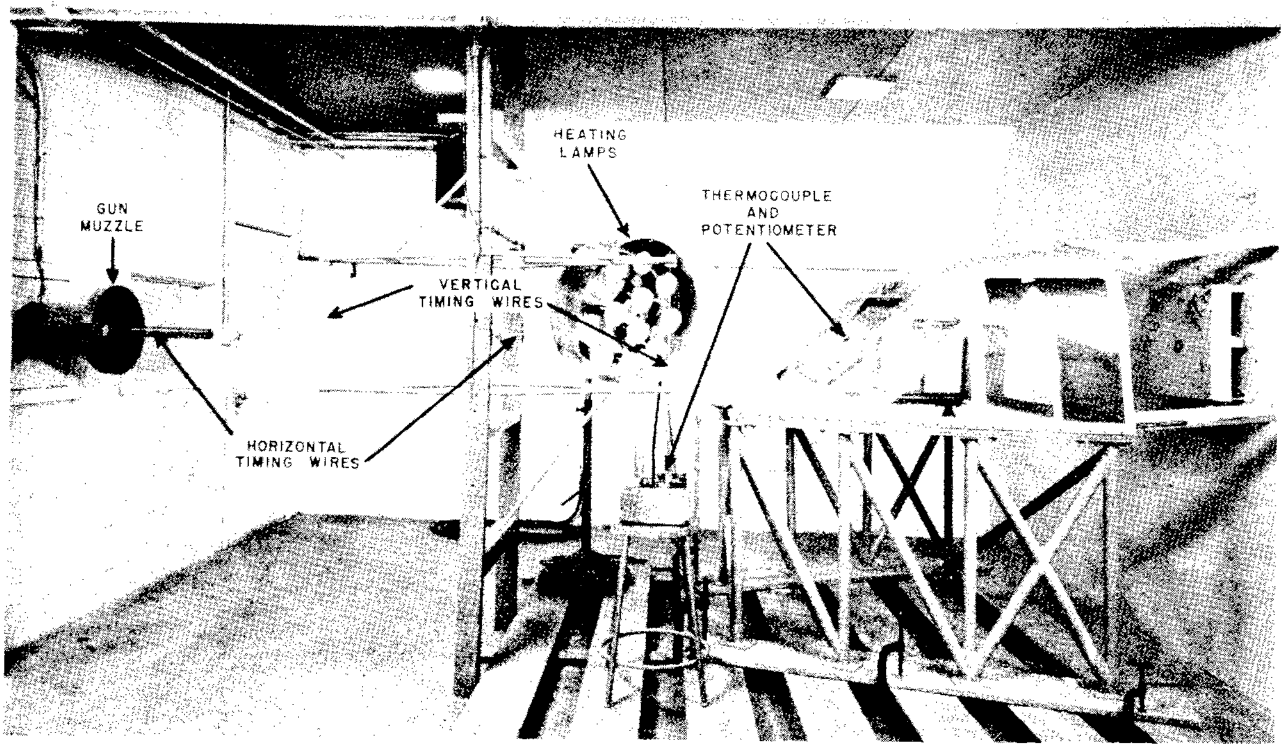


Fig. 5 Typical Cockpit Section in Position for Impact Tests

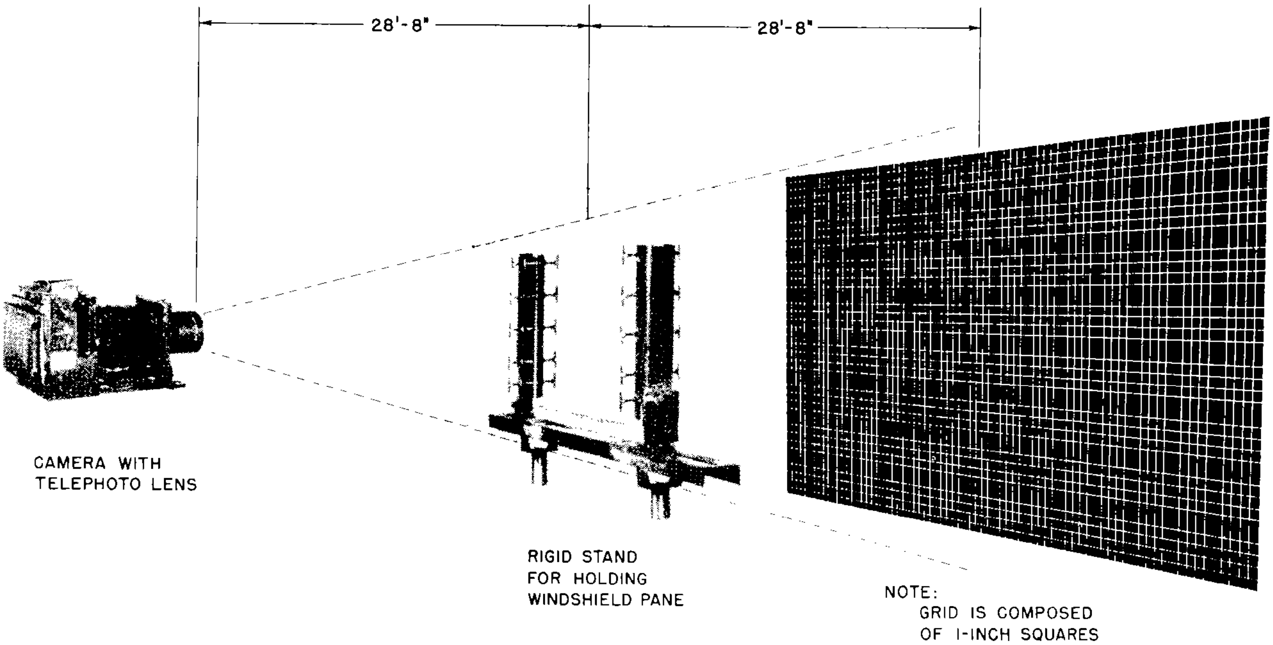


Fig. 6 Schematic View of Arrangement of Equipment Used in Making Optical Deviation Measurements of Windshield Panes

negative permits determination of the deviation at all points of the panel. Measurement of grid line slopes provides rates of change of deviation.

DESCRIPTION OF PANEL TYPES

A large variety of different types of windshield panel construction, materials, and

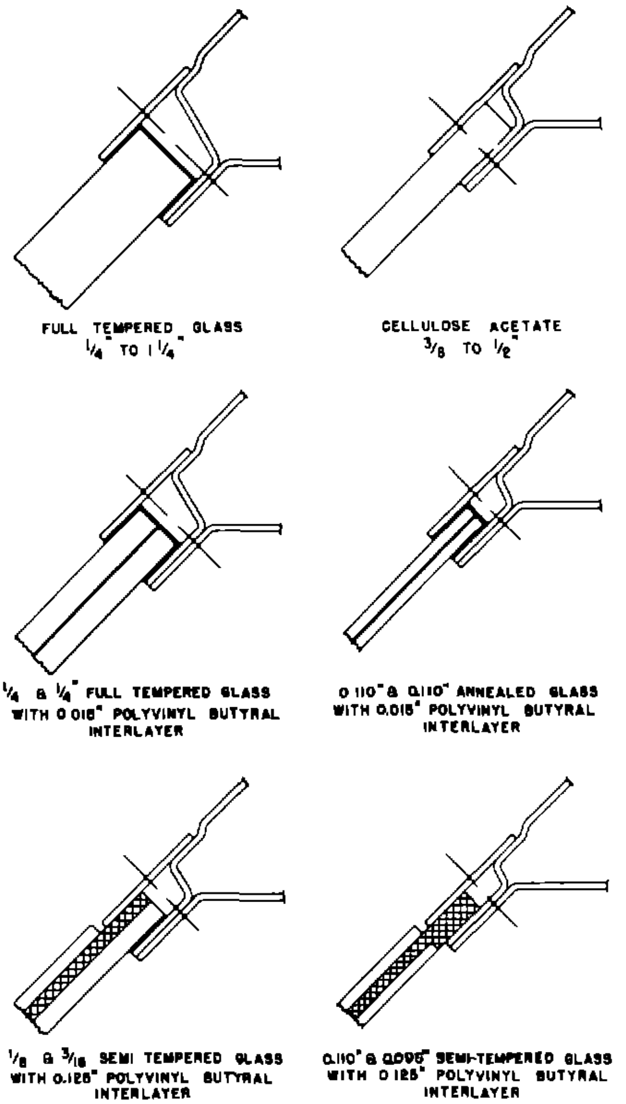


Fig 7 Type I Windshield Panel Single Pane With Rigid or Clamped Edge Type of Mounting

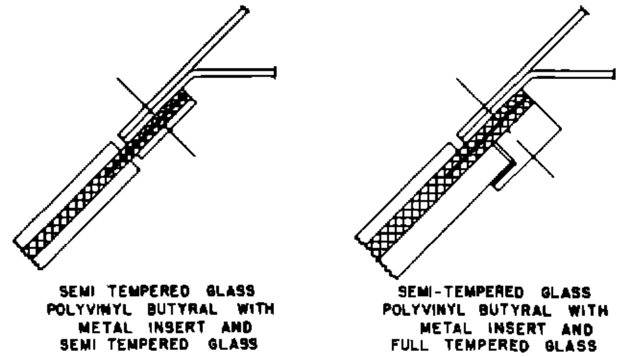


Fig 8 Type II Windshield Panel Single Pane With Flexible Bolted Edge Type of Mounting

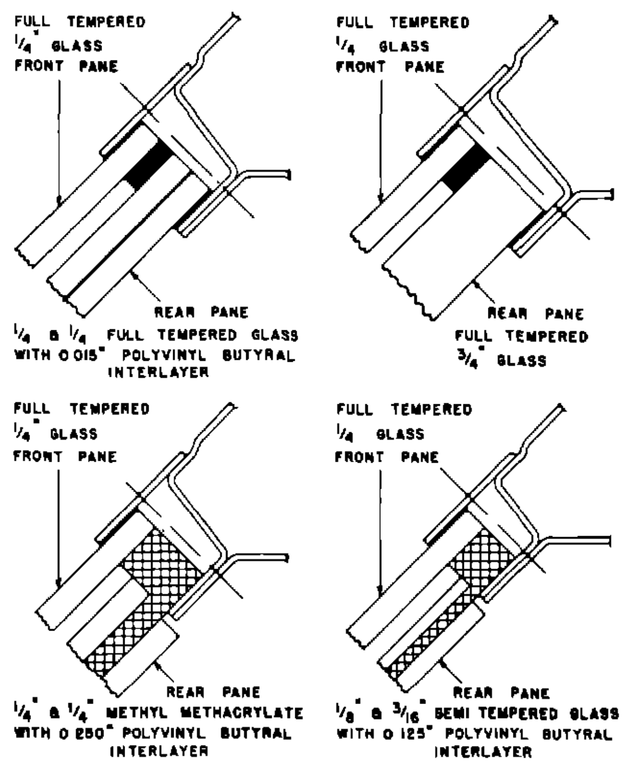


Fig 9 Type III Windshield Panel Double Pane With Rigid or Clamped Edge Type of Mounting

arrangements were included in the tests The various types may be separated into four principal classifications

(1) Single-pane installations with rigid or clamped edge mounting
(2) Single-pane installations with flexible bolted edge mounting
(3) Double-pane installations having rear pane with rigid edge.
(4) Double-pane installations having rear pane with flexible bolted edge mounting

Various typical installations representing each of the four classifications are shown schematically in Figs 7 to 10 A detailed description of principal variations of

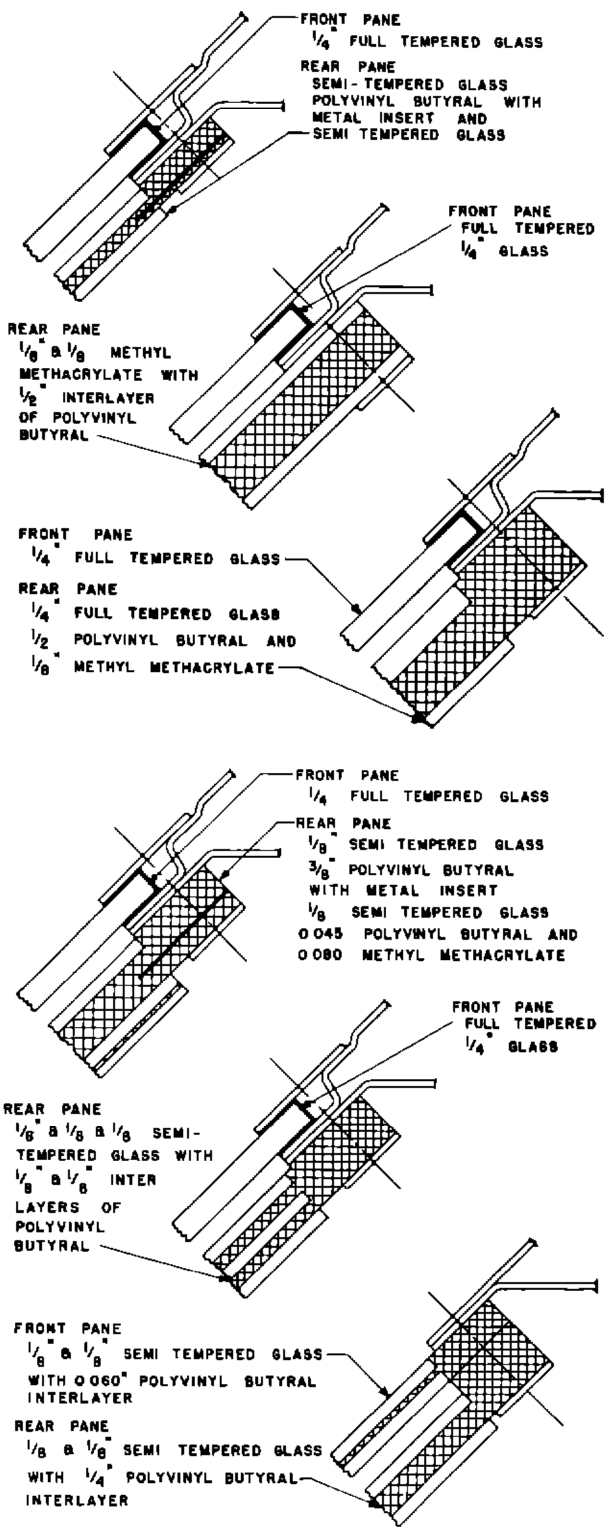


Fig 10 Type IV Windshield Panel Double Pane With Flexible Bolted Edge Rear Pane Type of Mounting

each type included in the tests is given in Tables I to IV

It will be seen from these tables that a large variety of panels have been tested, incorporating various combinations of annealed, semi-tempered and full-tempered glass, polyvinyl butyral, methyl methacrylate, and cellulose acetate In the interest of brevity, the term polyvinyl butyral will be at times referred to as butyral The panels have been tested in various types of mounting structures, and with considerable variation in details of construction

Included in the types of panels shown in Figs 7 to 10, and described in Tables I and II, are panels used for corner clear-vision windows, or for added windows above or below the windshield proper, in various practical installations

TEST RESULTS AND DISCUSSION

Impact Resistance of Windshield Panes

The penetration velocity, or velocity of bird carcass of specified weight which will barely cause failure of the windshield panel or immediate supporting structure and permit portions of the carcass to pass through, is shown in Tables I to IV as determined by test for each type and variation of windshield panel construction The angle of slope, temperature, and other important conditions of each test are also shown

Each value of penetration velocity given in Tables I to IV is generally based on three to four individual tests. The final value of penetration velocity taken in each case is the median value between the highest velocity where no penetration is obtained and the lowest velocity where penetration is obtained

Ideally, each value of penetration velocity should be based upon a large number of tests, and should be taken as the upper limit of a band of velocities which cause no penetration However, the expense and complication of each test, and the practical lack of need for extreme precision in the final test results, limit the number of individual tests which can be conducted Variation in individual test results is caused by uncontrollable variation in the properties of the test specimens, the attitude and elastic characteristics of the bird carcass, and the point of contact of the carcass on the test panel The magnitude of error in the values of penetration velocity given in Tables I to IV is estimated to be a maximum of about ±10 per cent

The significant facts shown by the data given in Tables I to IV in relation to the relative impact strength of various types and arrangements of windshield panels are briefly as follows

(1) The general type of pane which provides the greatest impact strength, when compared upon the basis of equal weight with other types of pane construction, is the laminated type pane with thick polyvinyl butyral plastic interlayer and with the flexible plastic edge bolted to the frame structure
(2) The thickness of a pane of one type construction strongly influences impact strength However, in a laminated glass-plastic panel with extended plastic edge, the thickness of the tempered glass faces has little effect on impact strength within reasonable limits, and the butyral plastic interlayer thickness has predominant effect
(3) An optimum temperature and plasticizer content exist for maximum impact strength of all panels in which plastic materials contribute appreciably to the strength. This effect is very pronounced in laminated, extended plastic edge type panes where the plastic provides the large portion of the impact strength of the pane
(4) In a double-pane arrangement, where a relatively thin front pane with good thermal transmission characteristics is used, the front pane contributes little to the impact strength of the combination. The type of front pane, within the limits permitted by the thermal requirements, is of little importance from the impact standpoint
(5) The more simple and uniform mounting possible for a single-pane installation appears to compensate for any small loss in strength associated with the absence of the front pane
(6) The angle of impact upon the windshield pane has great effect upon its impact strength, in general agreement with that expected from consideration of variation of force and velocity components with angle
(7) The general rigidity and energy absorbing characteristics of the windshield supporting structure have considerable effect upon the strength exhibited by the windshield pane. A structure which is highly elastic, or which undergoes moderate buckling, apparently causes lower forces to develop in the pane, with resultant delayed failure
(8) Impact upon sloped windshield panes is more severe for locations close to the aft edges or corners of the pane
(9) Size and shape of windshield pane have little effect upon impact strength over a considerable range

These various facts revealed by the data are discussed more completely herein

Type of Panel Construction

The evident superiority in the impact strength-weight relationship of the type of pane incorporating glass faces and a thick polyvinyl butyral plastic interlayer, which extends beyond the glass edges on all sides for bolting to the mounting frame, was demonstrated early in the test program This type of construction has appeared so advantageous throughout the test program that the large portion of the tests has been devoted to investigation of its particular characteristics

The use of the full-tempered glass pane has been suggested for aircraft windshields because of its excellent optical characteristics, its relative freedom from strength variation with temperature, and its freedom from cracking at impact velocities less than that required for complete failure. However, from weight consideration, the practical application of full-tempered glass panels for aircraft use appears to be limited to low speed aircraft or for side or corner window installations of high slope[3]

In Fig 11 is shown a comparison between the penetration velocities measured with various weights of butyral plastic laminated panes, and the penetration velocities of various weights of full-tempered glass plates It is indicated that to obtain the same impact resistance against a 4-lb bird carcass with panels supported in the standard steel frame, a full-tempered glass plate of approximately 260 per cent greater weight than the

[3]Pell Kangas "Impact Tests of Full-Tempered Glass Windshield Panels,' Technical Development Report No 71, August 1947

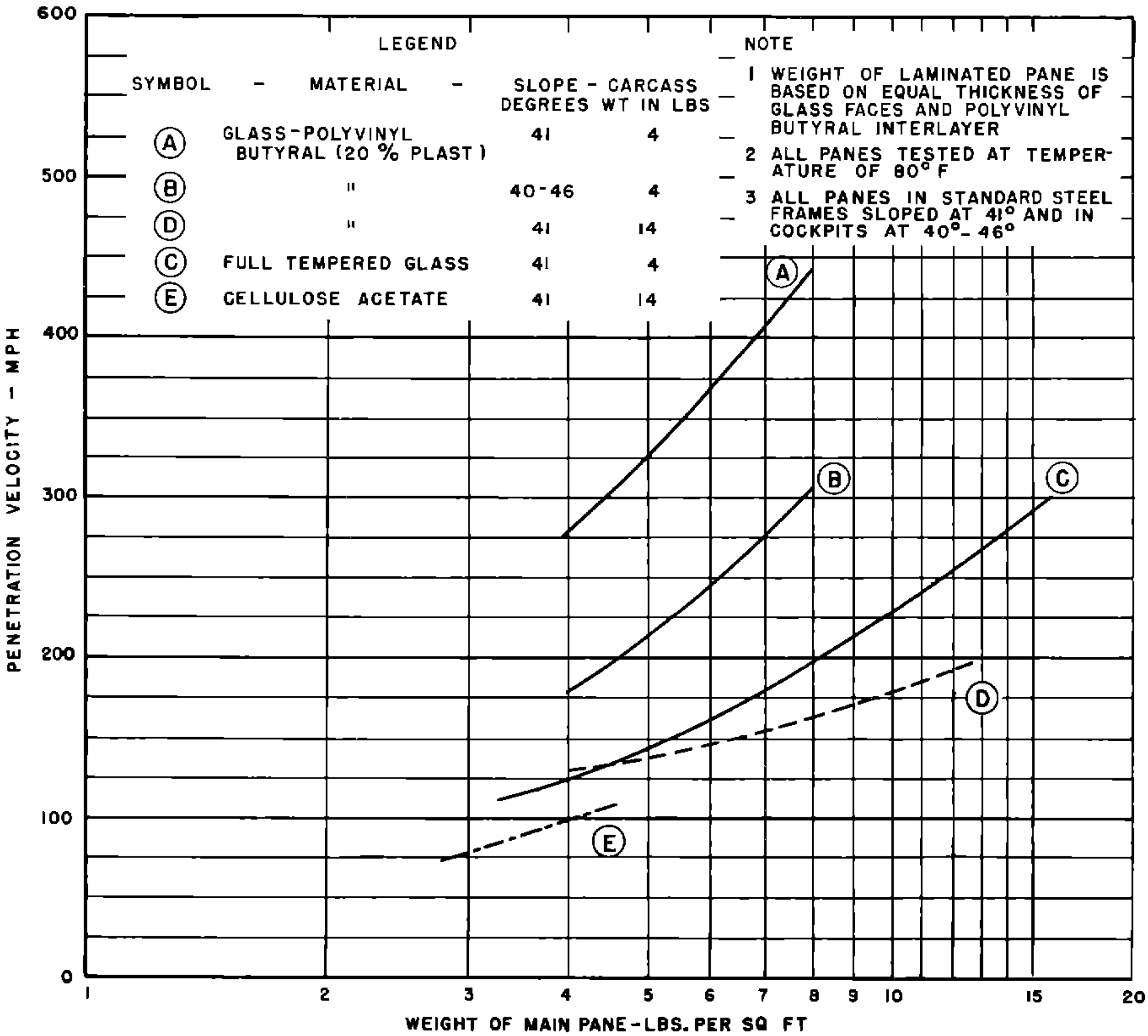


Fig 11 Variation of Penetration Velocity With Windshield Weight

extended plastic edge type is required for a penetration velocity of 300 mph

The reasons for the high impact strength exhibited by this type of panel construction may be readily explained Impact strength of any material is usually determined by its ability to provide large deformation under large loading forces without failure The combination of high load and large deformation result in high energy absorption In the present instance, the butyral plastic bolted to the frame around its periphery forms a flexible membrane, after failure of the glass faces, with relatively high tensile strength and elongation The energy absorbed by a sheet of such plastic before failure, therefore, is very large In Fig 12 is shown double-pane type windshield No 412 4 from Table IV, which utilized 0 188-in butyral interlayer in the rear panel and withstood penetration of a 4-lb carcass projected at a velocity of 300 mph at a pane temperature of 80° F

Characteristics of the polyvinyl butyral are illustrated by the curves shown in Fig 13 The data given, which were supplied by the

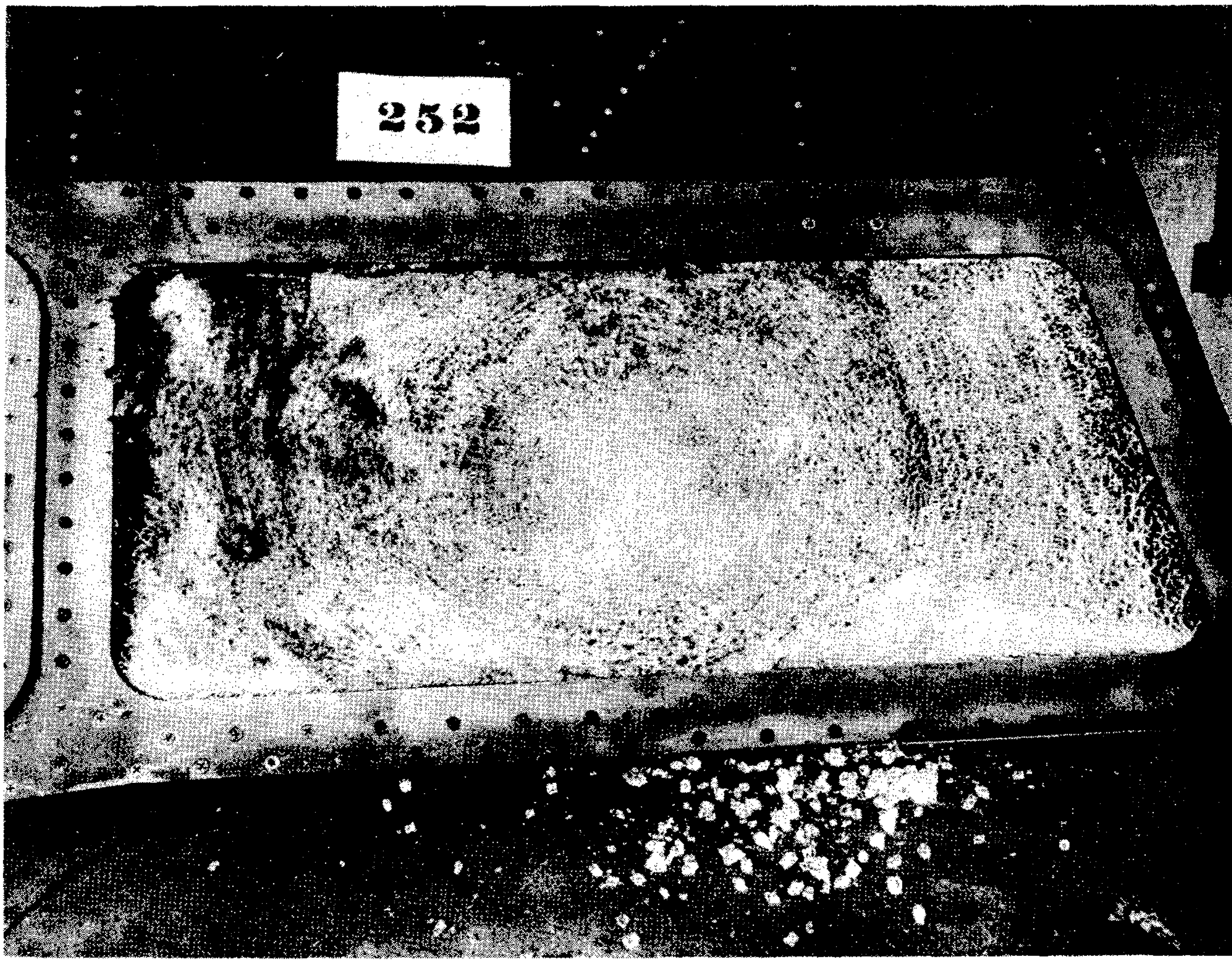


Fig. 12 Impact Test Resulting in Nonfailure of a Douglas DC-6 Windshield Utilizing 3/16-in. Polyvinyl Butyral Interlayer Tested With 4-lb. Chicken Carcass at 300 mph

Pittsburgh Plate Glass Company, are for conditions of low rate of load application, and therefore, do not apply directly to the high velocity impact involved in bird collision. The maximum value of toughness index, as derived by determining the product of per cent elongation and tensile strength from Fig. 13, occurs for butyral plastic with 20 per cent plasticizer content at about 14° F. The principal effect of high loading rate experienced in bird impact is indicated in Fig. 14, where the maximum strength of a 0.25-in. butyral plastic with 20 per cent plasticizer content tested with a 14-lb. bird carcass occurs at 110°F. When test temperatures below 80° F were used, the penetration velocity dropped rapidly because of the decreased elongation of the plastic at such temperatures. A complete study at these low temperatures has not yet been made.

Effect of Pane Thickness

Fig. 15 shows the effect of thickness upon impact strength of full-tempered glass plates, cellulose acetate sheets, and butyral plastic interlayers in the laminated extended plastic edge type panes. The thickness of the glass faces is not included in data concerning the latter type of pane because of the relatively small contribution of the glass to the impact strength of this combination.

In Fig. 15 are included data obtained with panes of the laminated extended plastic edge type tested both in aluminum alloy

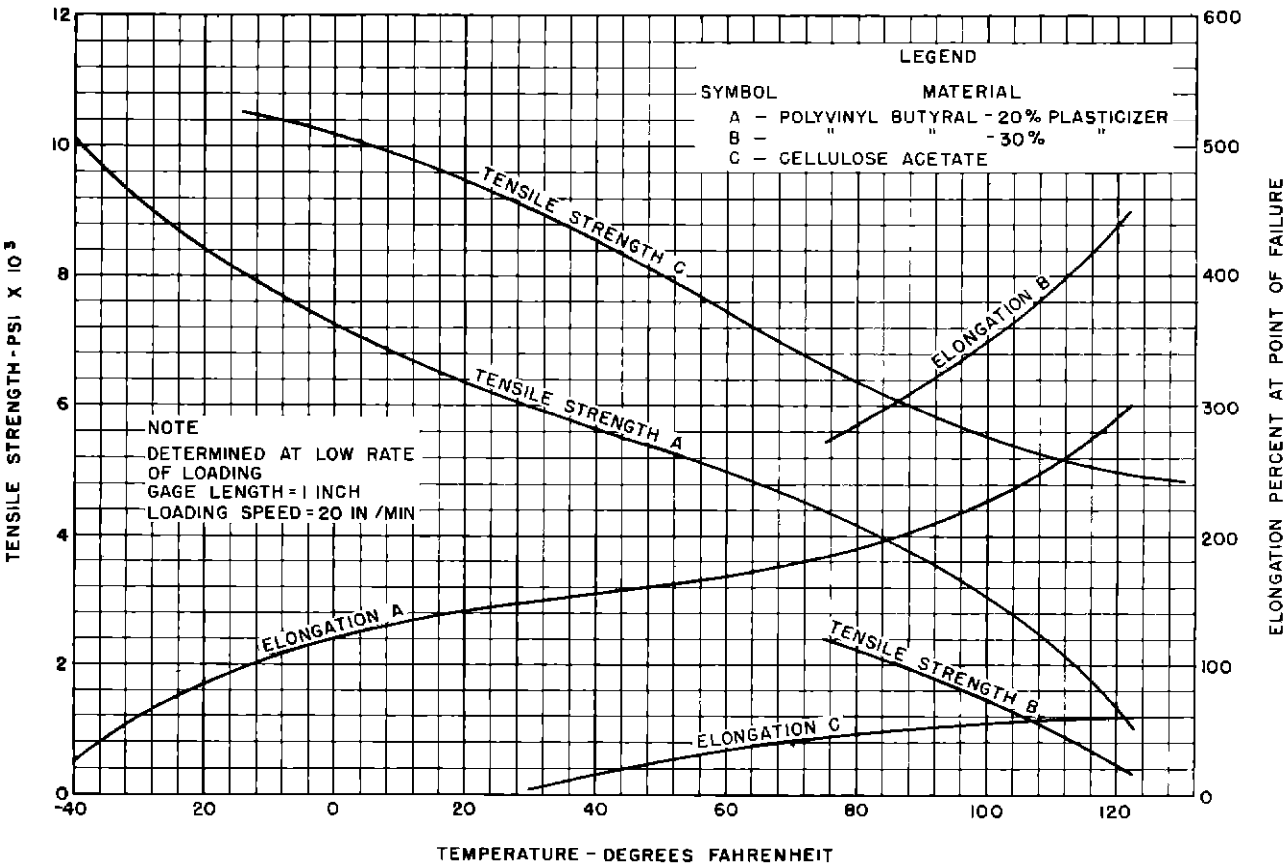


Fig 13 Variation of Tensile Strength and Elongation of Polyvinyl Butyral and Cellulose Acetate With Temperature

cockpit structures and in the simplified steel frames used for comparative tests It is shown that the panel penetration velocity, where failure occurs in the butyral plastic interlayer, varies approximately as the logarithm of the plastic thickness This can be expressed by the equation

$$T = Ke^{\frac{v}{c}}$$

where

T = thickness of vinyl plastic in inches
v = penetration velocity of windshield panel in mph
K & c = constants

For the three curves in Fig 15 involving laminated panels, the following constants may be substituted in the above expression which will indicate the approximate slope and position of each curve

Structure Supporting Windshield Test Panel	Windshield Slope (degrees)	Weight of Carcass (lbs)	Value of K	Value of c
Standard Steel Frame	41	4	0 0372	230 5
Cockpit	40-46	4	0 0498	180 0
Standard Steel Frame	41	14	0 0121	54 6

In the case of the full-tempered glass panels, a more complete expression was derived This expression also includes the effect of varying the windshield slope from 41° to 60° and may be stated as follows

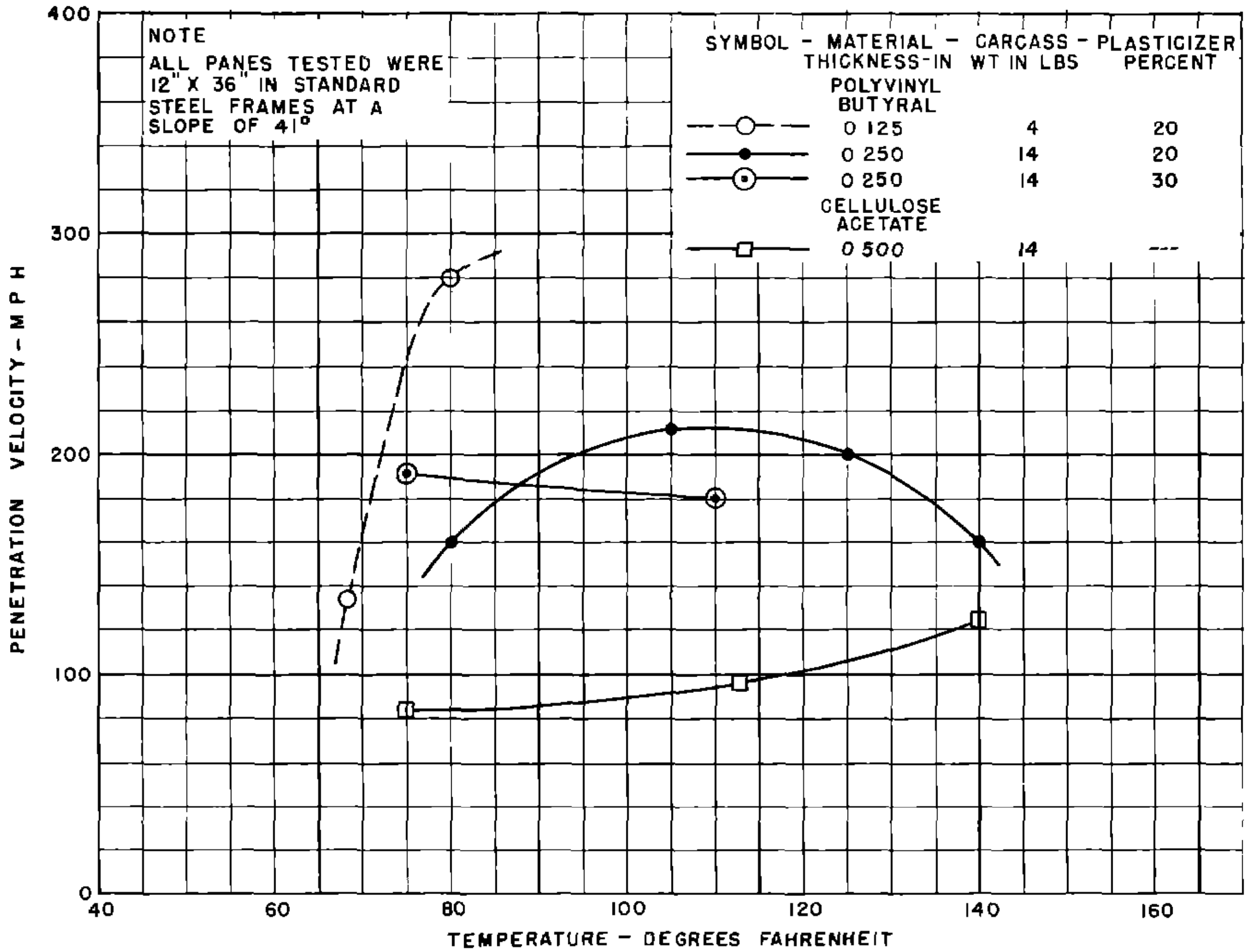


Fig 14 Variation of Penetration Velocity With Windshield Temperature

$$T = 0\ 136\ (1-0\ 348\ \cos\theta)\ e^{\frac{v\ \cos\theta}{87\ 3}}$$

where

T = thickness of full-tempered glass pane in inches

v = penetration velocity in mph

θ = total angle of slope of panel in degrees

The considerable decrease in penetration velocity shown in Fig 15 for laminated extended butyral plastic edge type panes when mounted in cockpit structures, as compared with identical panes mounted in the standard steel frames, is associated with effect of structural rigidity and will be discussed in a later section The values given for the panels tested in cockpit structures represent a moderate variation in panel size and shape, angle of impact, and type of mounting However, in the cases chosen, the effect of these variables was secondary to the effect of pane thickness

Plastic Temperature and Plasticizer Content

As previously discussed in connection with Fig 13, the physical characteristics of polyvinyl butyral resin used for windshield construction are affected considerably by temperature An effect similar to that caused by temperature variation also is produced by variation in the plasticizer content of the resin Thus, a resin of specific plasticizer content may be brought to its optimum energy absorbing state by correct temperature adjustment, and conversely a resin which will be used at a definite temperature may be caused to have its optimum impact resisting proper-

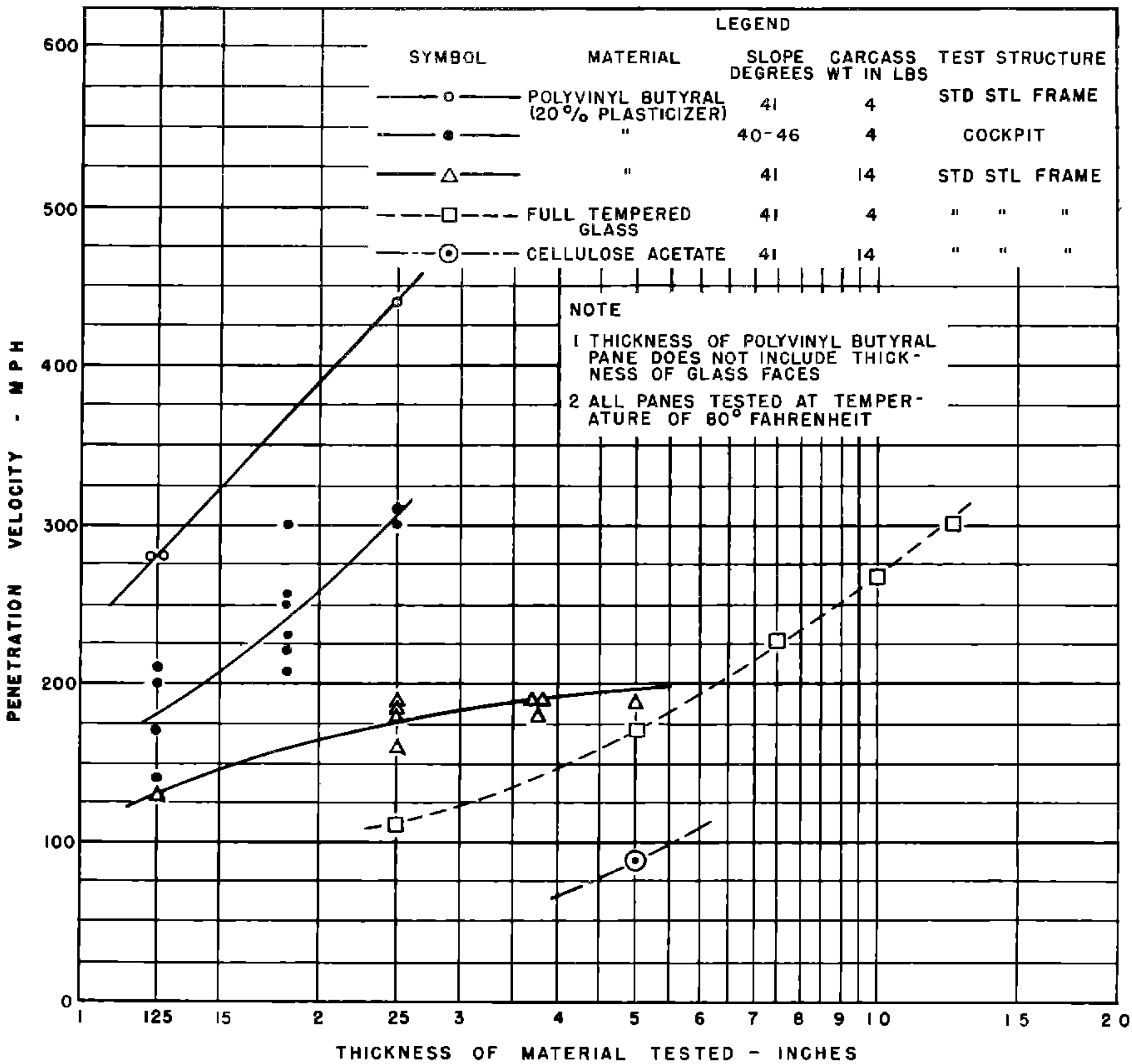


Fig 15 Variation of Penetration Velocity With Windshield Thickness

ties at this temperature by adjustment of plasticizer content

This relationship is shown bv the data given in Fig 14 It is seen that with 0 25-in thick butyral plastic of 20 per cent plasticizer content tested with a 14-lb bird carcass, the maximum impact strength is obtained at about 110° F With 30 per cent plasticizer, the optimum temperature has not been determined accurately but test results indicate it to be not more than 80° F With 12 per cent plasticizer, the optimum temperature appears to increase considerably, although insufficient data have been obtained for a complete determination

It is evident that with a given plasticizer content, the panel impact strength is high in value within a particular range of temperatures At lower and higher temperatures beyond this range, the impact strength decreases at a very rapid rate At 68° F the impact strength of polyvinvl butyral with 20 per cent plasticizer content, as measured in terms of penetration velocity of 0 125-in plastic with a 4-lb carcass, is only about one-half the value at 80° F

It is indicated by the data given in Figs 13 and 14 that advantage might accrue from use of highly plasticized resin for low temperature conditions However, consideration must be given to the very low strength and high elongation of such material under any high temperature condition which may be encountered For practical use, butyral plastic with a 20 per cent plasticizer content has been considered an optimum value for aircraft windshield application, especially where high temperatures associated with hot-air de-icing methods exist However, under special temperature conditions, a different plasticizer content might be advantageous and also practical

The data given in Fig 14 also show that aircraft type cellulose acetate, usable for windshield material on light aircraft, increases rapidly in resistance to impact as the temperature is increased above 120° F It is indicated that cellulose acetate of higher plasticizer content would exhibit high impact strength at lower temperatures

Impact Strength of Front De-icing Pane in Double-Pane Arrangement

The thickness and composition of the front de-icing pane of a double-pane windshield arrangement normally are limited by requirement for good thermal transmission characteristics In particular, this requirement places severe limitation upon the use of a plastic such as butyral in this pane, as the thermal transmission of butyral is only about one-fifth that of glass Accordingly, it may be expected that the front pane can contribute only a small portion of the impact strength of the combination

Three types of front pane construction were included in the tests, as shown in Fig 16 Specific data were not obtained to determine the precise effect of each type of front pane construction, but it was evident from the test results that the front pane had small effect upon the impact strength For example, a 0 25-in full-tempered glass front pane adds little if any strength to a laminated glass-plastic type rear pane, and a laminated front pane with 0 060-in butyral plastic interlayer adds about 10 per cent to the

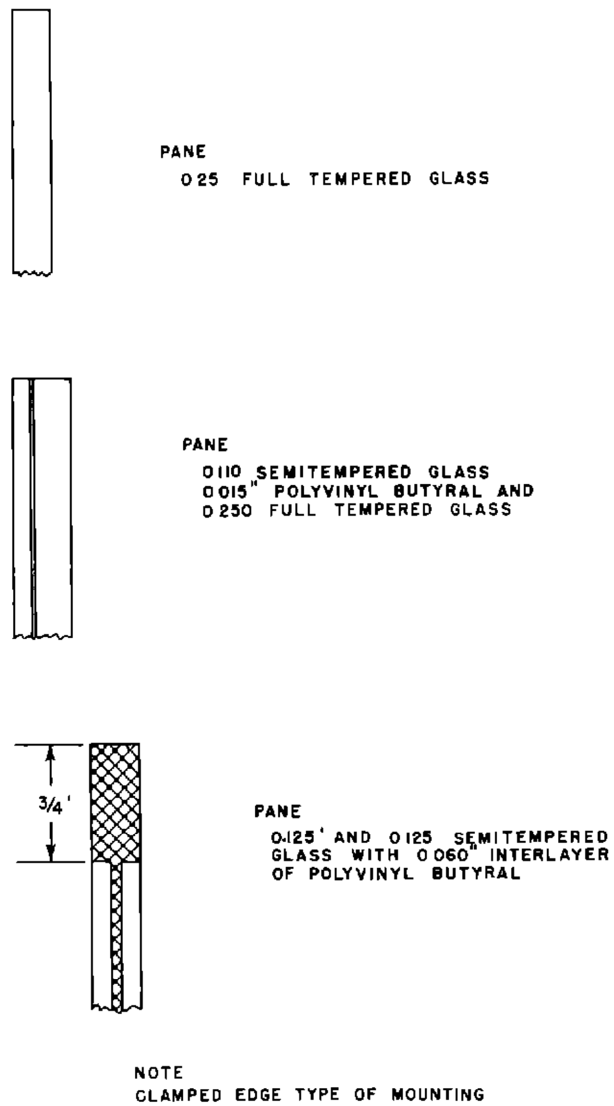


Fig 16 Edge Detail of Various Front Panes Tested in Double Pane Type Windshields

strength of a rear pane containing 0 25-in butyral plastic thickness

The tests upon which these conclusions are based were carried out with bird carcass weights of 4 to 16 pounds It is indicated from flight accident experience, and from theoretical considerations, that a front pane of 0 25-in full-tempered glass provides a high degree of protection against small birds of less than 1-lb weight In such experience, at common aircraft velocities, the bird carcass is repelled with no cracking or damage to the windshield panel

Effect of Mounting Structure Upon Panel Impact Strength

A detailed discussion of windshield supporting structures and arrangements is given in a later section of this report However, it has been observed that the impact strength, or penetration velocity, of a given type of windshield panel will vary over a considerable range of values, depending upon the particular structure used No detailed analysis or specific measurements were made in this particular connection, but various general observations may be discussed

It is shown in Figs 11 and 15 that an approximate 125 mph decrease in penetration velocity exists for windshield panels of identical plastic thickness when mounted in cockpit structures rather than in the standard steel frame used for comparative tests This decrease in penetration velocity may be attributed to

(1) an increase in the elastic rigidity, and a decrease in ease of structural buckling, in the cockpit structure
(2) variation in the elastic and buckling characteristics of the cockpit structure around different portions of the windshield, resulting in localized stresses in the panel
(3) variation in the uniformity of bolt attachment of the panel to the cockpit structure, resulting in localized stresses in the panel

All of these factors are of importance in determining impact strength of the panel The characteristics of the standard steel frame used in the tests were, in all of the above respects, such as to tend toward maximum panel strength

As several of the cockpit structures tested provided fairly uniform structural support and attachment of the windshield panel, it may be concluded that the elastic and buckling characteristics of the supporting structure contribute a fairly large portion of the total panel strength difference noted

Insufficient cockpit structures were tested, with approximately equivalent panel mounting angle and widely different structural rigidity, to permit measurement of the effect of such structural differences The cockpit data included in Figs 11 and 15 were for cockpits of large aircraft with a relatively rigid structure designed to withstand internal pressure loads

Effect of Angle of Impact Upon Panel Strength

In Fig 17 are shown data obtained with panes of identical plastic thickness tested in the standard steel frame at various angles of impact, and other panes of the same thickness tested in various cockpit structures in which the angle of mounting varied Test results obtained with full-tempered glass panes of different thickness are also shown

Although known advantages exist from the standpoint of impact resistance in decreasing the angle of impact by suitable design and layout of the windshield in the airplane, consideration must be given to the resulting increase in optical distortion and decrease in general visibility

An exception to the general rule for variation of penetration velocity with impact angle of laminated extended plastic edge panes, as shown in Fig 17, is found in the case of very small panes and where impact occurs at the aft edge of a sloped large pane In such cases, at some minimum velocity the bird carcass tends to crack the glass faces and to pocket into the plastic interlayer as the latter stretches Because of the proximity of a frame member to the rear, the carcass cannot slide off the sloped panel Under such circumstances, the penetration velocity is to a large degree independent of the windshield angle

Effect of Location of Impact on Panel

The penetration velocity of a windshield of the laminated flexible bolted edge type will vary over a considerable range of values depending upon the location of the impact upon the panel Some data in this connection are given in Table IV However, observations of a large number of tests indicate that the quantitative effect produced by variation of impact location depends upon several factors, and the effect can be described only with regard to general tendencies

The cause of such variation is partially explained in the previous section, where it was shown that impact just forward of an aft edge of the windshield panel will result in a local pocketing of the bird carcass with the adjacent rigid structural member, preventing sliding action In addition to this factor, impact near any of the edges of the panel results in large and localized shearing and tension stresses in the plastic interlayer along the edge of the panel in the immediate vicinity of the impact

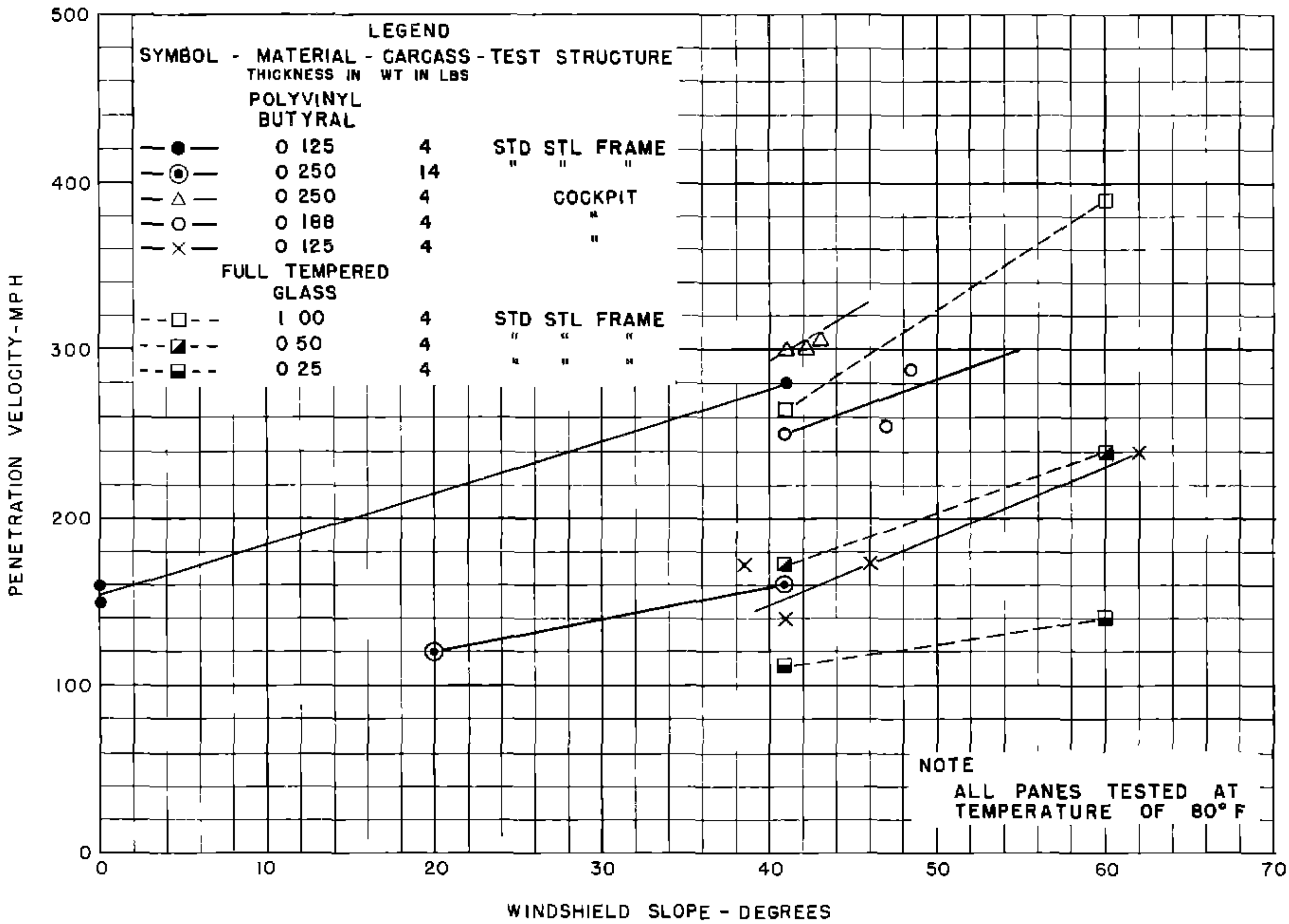


Fig 17 Variation of Penetration Velocity With Windshield Slope

The penetration velocity of a panel of the laminated flexible bolted edge type will be a maximum for impact at the center of the panel, a minimum for impact close to the aft edge or edges, and of intermediate value for impact close to other edges For the common type of panel arrangement with both the horizontal and vertical axes sloped, the location of impact for minimum penetration velocity will be close to the upper outboard corner

This relationship is shown in the data of Table IV, Test Nos 407 1, 407 2 and 407 3, wherein a double-pane arrangement with 0 25-in butyral plastic interlayer in the rear pane, with the horizontal axis sloped 38° and the vertical axis sloped 17°, failed at 160 mph with impact of a 14-lb carcass at the center of the pane Failure was obtained at 110 mph with impact 5 5 in from the aft end, and at 150 mph with impact 5 5 in from the forward edge

The magnitude of the variation of penetration velocity with impact location will depend upon the angle of impact and upon the rigidity of the frame structure In general, a smaller angle of impact and a greater structural rigidity will increase the magnitude of this variation

Effect of Size and Shape of Panel Upon Impact Strength

Special tests were carried out to determine the effect of variation of size and shape of windshield panel upon impact strength These tests were conducted with laminated panels incorporating 0 125-in butyral plastic, and with a 4-lb bird carcass It was found that variation of flat-panel shape from 1 by 1 foot square to 1 by 3 foot rectangle, and changing the area of square panels by a factor of four, appears to cause no appreciable change in penetration velocity for impact normal to and at the center of the panel. However, a 2 by 2 foot panel exhibited 40 per cent greater impact strength than the lesser sized panels when tested at an angle of slope of 41° (see Table II, Type 201). Additional tests are necessary to verify preliminary results and determine further the combined effect of angle and variation of panel shape.

A corroboration of the tests of the flat 2 by 2 foot panel as described in the preceding paragraph is indicated in tests performed on relatively large, highly sloped, curved, laminated panes which were attached to the cockpit structure by means of the clamped edge type of mounting. Data concerning this type of panel are given in Table I for Type No. 111.1 The unusually high strength of this panel with only clamped edge mounting may be partially explained by the large angle of slope of 63°, but the high strength also undoubtedly is associated with the large panel size. Failure of the panel was of a local nature and, except where impact occurred close to one edge of the pane, the tensile forces developed in the plastic interlayer were so small for each unit length of the large edge dimensions that the panel did not pull from the frame as ordinarily occurred with smaller panels of this type.

A high-speed motion picture study of the result of impact occurring near the forward edge of windshield Type 111.1 is shown in Fig. 18. This illustrates the failure of the clamped edge type of mounting. In this case the carcass is deflected upward because of the unusually great slope of the windshield. The formation of a cloud of glass splinters is also evident as a reaction to the impact. Comparable splintering of the inner face into the cockpit also occurs.

Edge Mounting of Laminated Flexible Bolted Edge Type Panes

In general, the test results have shown that the edge attachment of a laminated flexible bolted edge type pane forms the most critical part of the installation with regard to impact strength. The method of transmitting tensile and shear stresses from the plastic interlayer of the panel into the metal structure is of primary importance.

The type of failure occurring at excessive carcass velocities in a windshield panel with adequate edge mounting is shown in Fig. 19, with the plastic interlayer absorbing

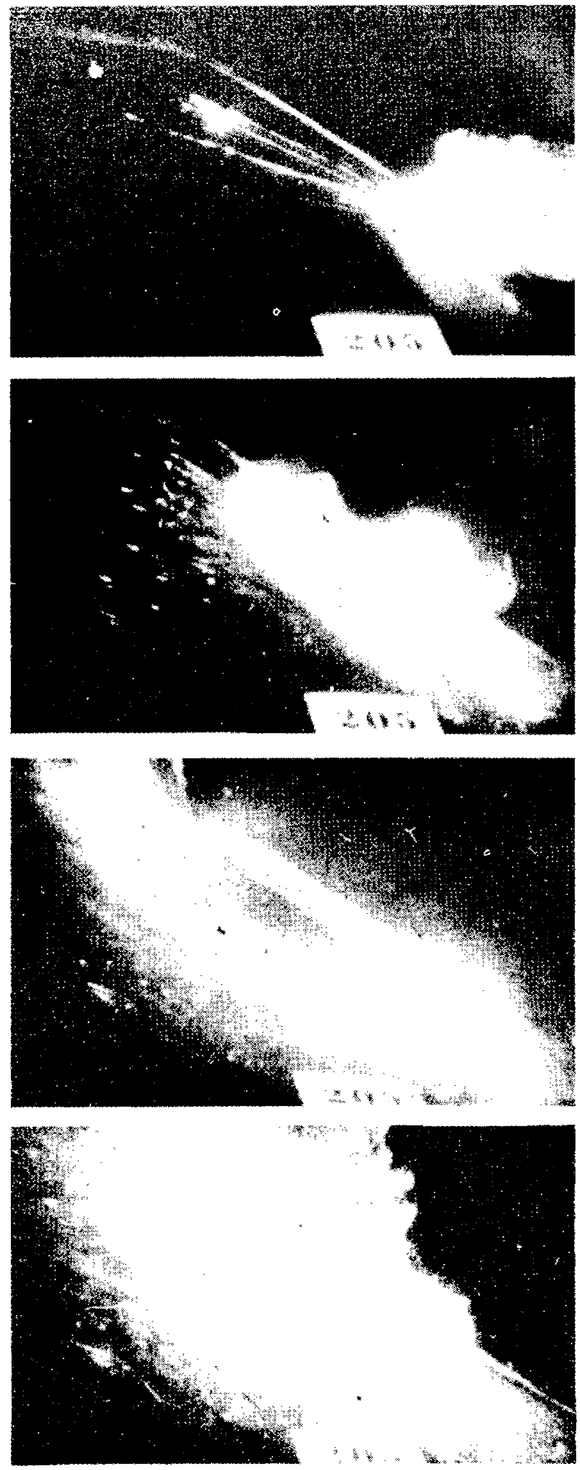


Fig. 18 Single Frames From a High Speed Motion Picture Film of Impact Test on Curtiss-Wright C46A Cockpit. Time Sequences Measured From First Frame are 0.004, 0.013, and 0.082 Seconds

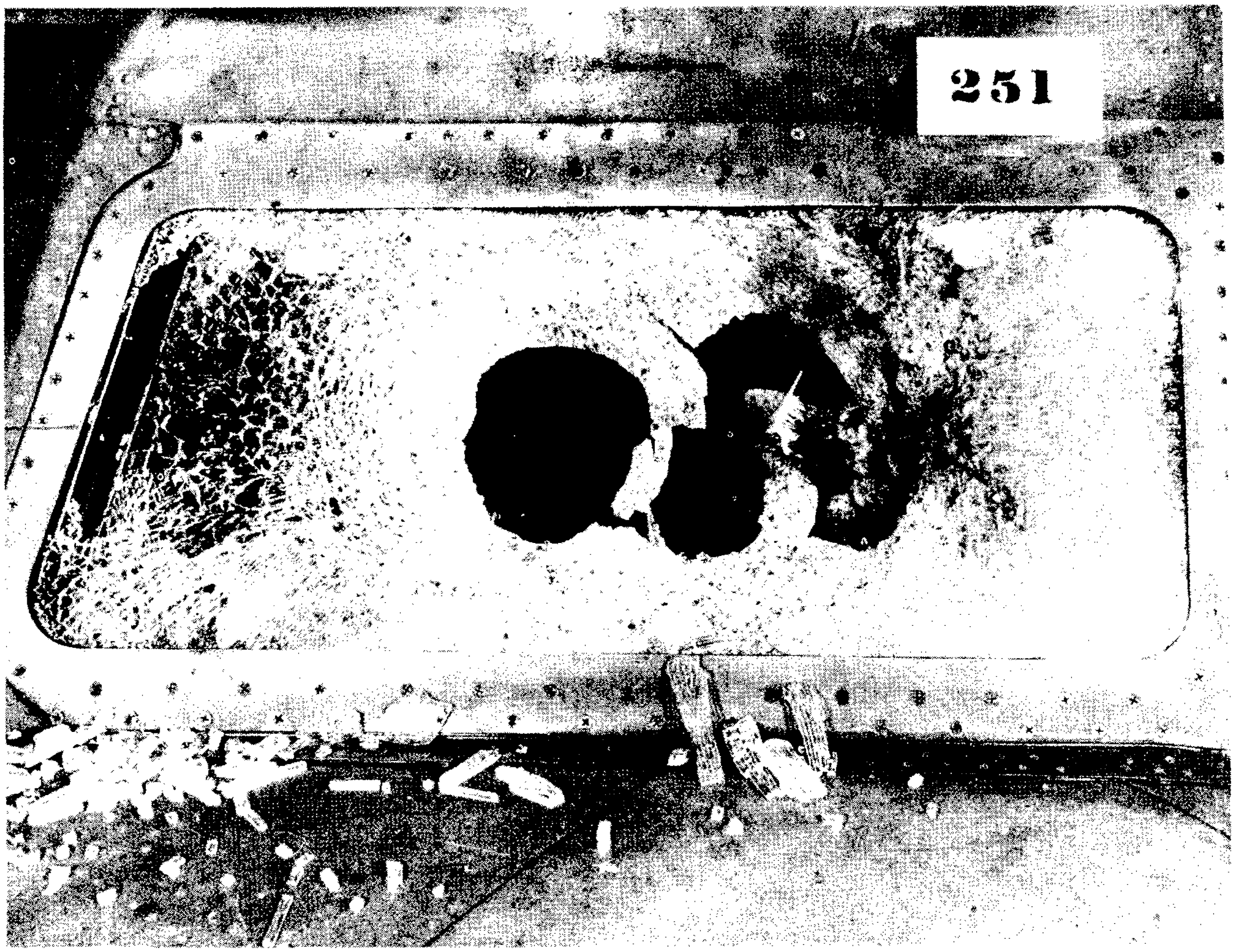


Fig. 19 Example of Failure at Center of Laminated Pane With Polyvinyl Butyral Interlayer

maximum energy before tearing. This type of failure indicates optimum butyral plastic temperature and sufficient strength in the edge mounting of the panel and the frame attaching the panel to the cockpit structure.

In Fig. 20 is shown a typical edge mounting arrangement for panels of such type. The important variables in the method of edge attachment are (a) thickness, width, and type of metal insert strip, and (b) diameter, type, spacing, and edge distance of mounting bolts.

(a) Metal Insert

Aluminum alloy 24S-T is commonly used as the material for the metal insert strip, although steel alloys also may be used. The thickness of the metal insert strip is critical. If the strip is too thin, the mounting bolts passing through the strip will tear through the edge to cause failure. Too great a thickness of the metal insert, with corresponding stiffness and decreased butyral plastic thickness in the edge section, results in shearing of the plastic interlayer along the inside edge of the insert, as is shown in Fig. 21. The optimum thickness of the metal insert is related directly to the thickness of the plastic interlayer.

In Table V are classified, according to type of failure, windshield panels that were tested both in cockpits and the standard steel frame. The first category of failures, where the extended plastic edge sheared at

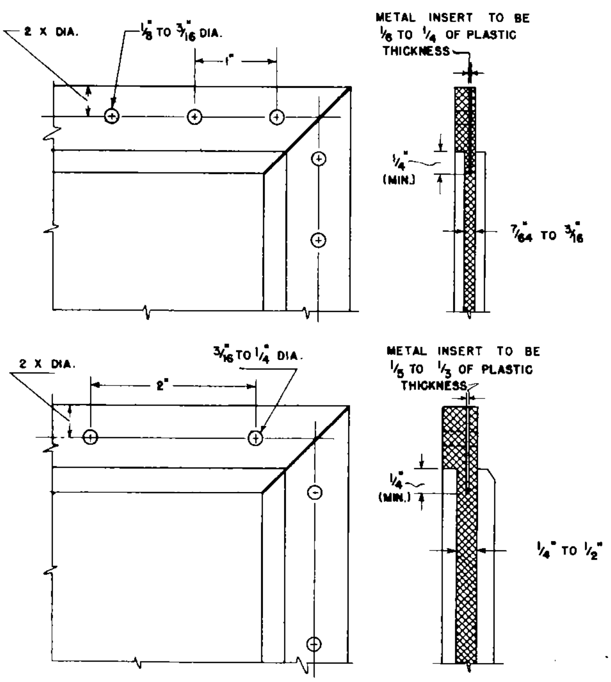


Fig. 20 Design Requirements for Edge Mounting of Laminated Panes With Polyvinyl Butyral Interlayer

the mounting bolts, indicates either lack of insert or insufficient thickness of insert when the mounting bolt size, spacing, and edge distance are satisfactory. An example of failure due to lack of adequate insert thickness is shown in Fig. 22.

In the second category of failures in Table V are shown some test results where the butyral plastic laminated pane sheared at the line of metal insert, indicating in several cases excessive thickness in the metal insert.

This type of failure is shown in Fig. 21. Rigidity of the supporting structure, and lack of adequate width of the insert so that it does not extend a sufficient distance between the glass faces, also contribute to this type of failure. The effect of rigidity of the supporting structure will be discussed later.

It may be concluded that the thickness of 24S-T aluminum alloy metal insert strip should be between one-sixth and one-quarter

Fig. 21 Example of Failure Resulting From Impact Test Where Plastic Interlayer Sheared Along Inner Edge of Metal Insert

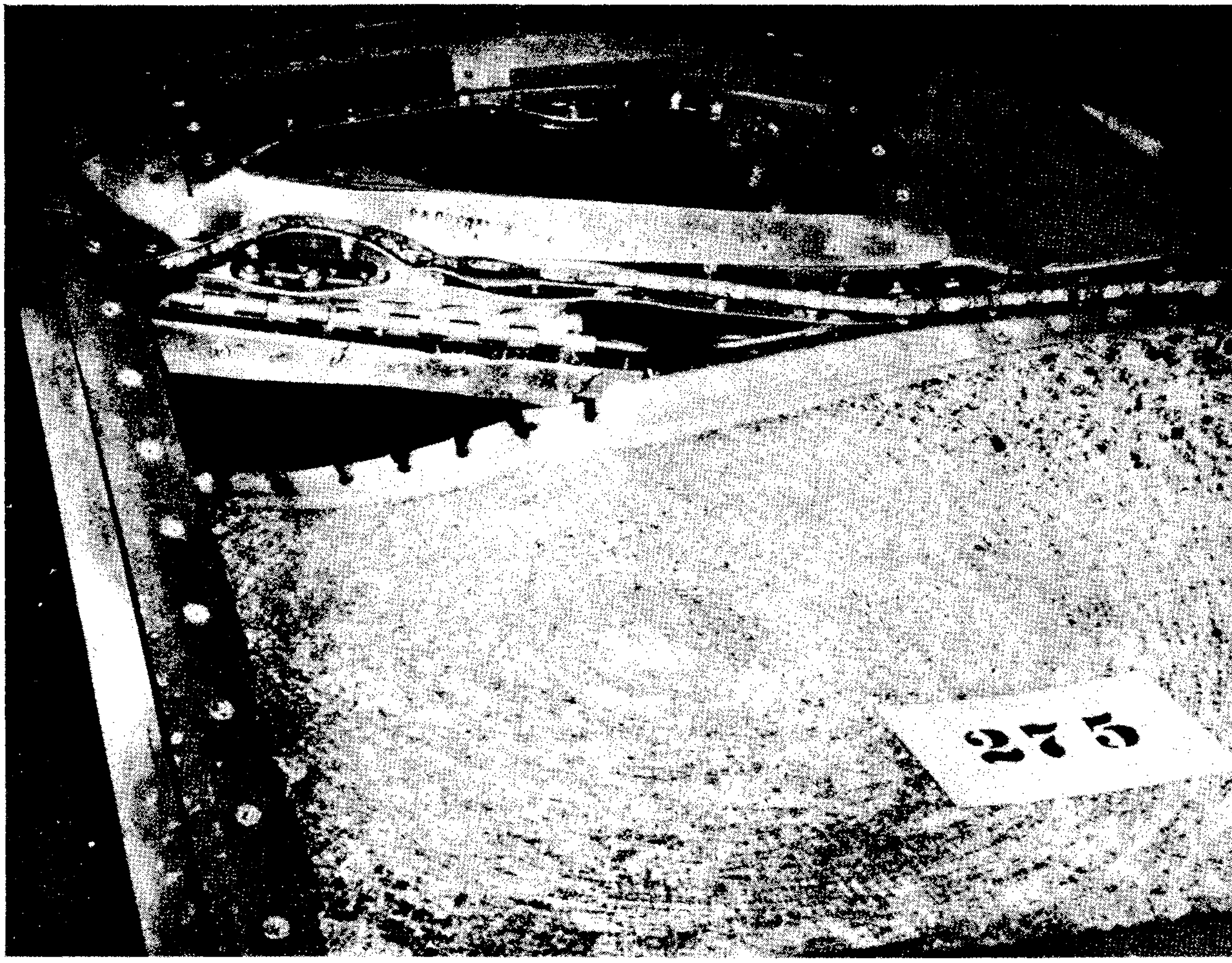


Fig. 22 Example of Failure Resulting From Impact Test Where Plastic Edge and Metal Insert Sheared at the Mounting Bolts

the thickness of the butyral plastic interlayer, where the plastic interlayer thickness is 0.188-in. or less. It appears desirable to use a minimum thickness of metal insert for the thinner plastic interlayers.

With regard to width of the metal insert strip, it has been found that satisfactory results are obtained if the metal insert strip extends at least 0.25-in. between the two glass faces of the pane. If the strip does not extend between both glass faces in this manner, a strong tendency exists for failure of the plastic interlayer in shear along the inside edge of the strip.

(b) Mounting Bolt Size and Spacing

The loads developed by bird impact on a windshield pane of the laminated bolted edge type are transmitted to the aircraft structure through the bolts which attach the pane to the frame. The type, size, and spacing of such bolts, therefore, are of considerable importance in determining the impact strength of the installation.

There are shown in Table V data covering test results obtained with various mounting bolt arrangements. The data were secured with various panel thicknesses and mounting structures.

Bolt arrangements shown in Table VI for different butyral plastic interlayer thickness, or equivalent arrangements, have been indicated by test to be satisfactory. The values given in Table VI are average figures and will be conservative for panels with very high angle of slope or with very resilient mounting structure, and probably represent insufficient strength for extremely small panel slope or extremely rigid structure It is generally established that the bolt size and distance between bolts should provide strength equivalent to a 2-in spacing of No 10 steel bolts (100,000 psi H T) for 0 125-in plastic interlayer thickness, and a 1-in spacing of identical bolts for a 0 25-in interlayer thickness

In order to obtain the necessary strength in the bolt attachment, it appears desirable to use small bolts with close spacing, rather than large bolts with wide spacing but of equivalent total strength, in order to secure the most uniform load distribution in the plastic interlayer and metal insert

The forces on the mounting bolts are a combination of shear and tension forces, but the relative magnitudes of the two force components depend upon the ease of rotation of the frame structure, the stiffness of the glass, and other factors

Adequate distance between the center-line of the bolts and the edge of the panel is of importance in preventing the mounting bolts from shearing through the plastic edge of the panel The minimum suitable edge distance is a function of metal insert thickness and other factors, but it appears that a distance between the bolt center-line and the edge of the pane of not less than twice the bolt diameter will provide satisfactory strength

Windshield Frame, Sill, and Post Design

The design of a suitable mounting and supporting structure for an impact resistant windshield installation presents a complex problem This is true particularly with a double-pane de-icing type windshield where it is usually required that the rear pane, in which most of the impact strength is incorporated, should be mounted so as to be readily opened in flight for cleaning purposes

As each windshield installation design varies widely in detail, and as no complete and precise quantitative determination has yet been made of the forces existing during bird collision, the present report includes only general conclusions in this connection, and data relating to specific practical designs which may be generally applicable to other designs An example of failure of supporting structure resulting from impact on the windshield panel is shown in Fig 23

The following conclusions have been drawn from general observation and analysis of the test results

(a) Tests made upon various cockpit installations indicate that a relatively elastic structure which buckles readily possesses better impact characteristics than a heavy rigid structure No heavy reinforcement of a cockpit structure, such as added sheet stiffeners in the canopy, appears necessary for bird collision resistance except in very light structures Principal points of failure in the structure are usually in the windshield frame, in the attachment of the frame to the sills and posts, and the attachment of sills and posts to the primary structure

A uniform structural rigidity around the windshield appears desirable to eliminate sections of high shear stress concentration in the butyral plastic interlayer of the panel

(b) No apparent advantage exists in utilizing heavy rigid posts at the ends of the windshield panel, or between panels, except to reduce glass cracking in panels adjacent to the point of impact However, such posts may fail if their attachment to the structure possesses insufficient strength

(c) The rear pane of a double-pane windshield installation is required to possess high impact strength, and also is ordinarily required to be readily removable in flight Some examples of the attachment to the structure of double-pane installations tested are shown in Figs 24 to 29, and the point of apparent initial failure of the attachment is indicated

The conclusions drawn from tests of a large number of such installations are as follows

(1) The windshield frame, attached to the edge of the pane, should be as continuous as possible, particularly at corners, and should possess sufficient stiffness to transmit the imposed loads from the panel mounting bolts to the points of attachment of the frame to the structure without serious deformation

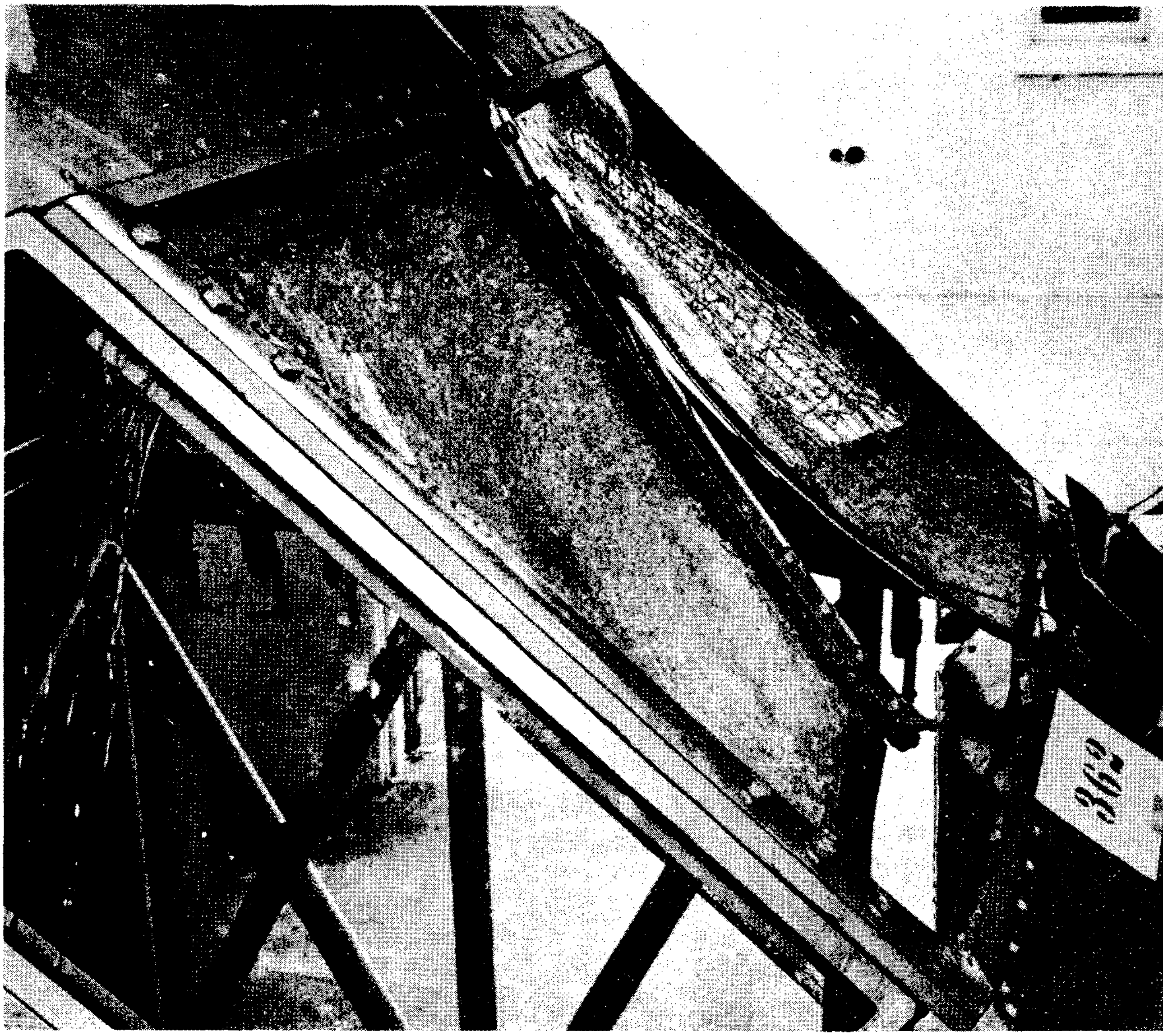
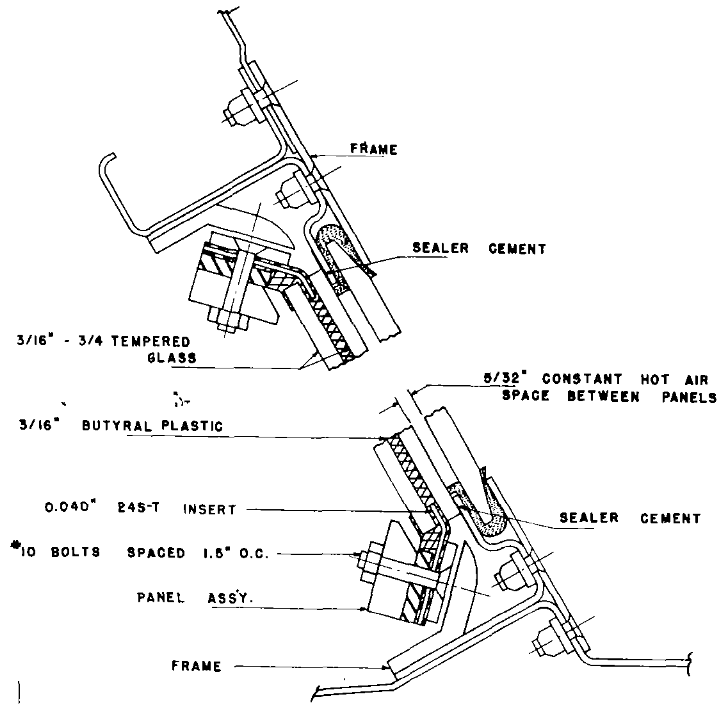


Fig. 23 Example of Failure Resulting From Impact Test of the Structure Supporting the Windshield Frame

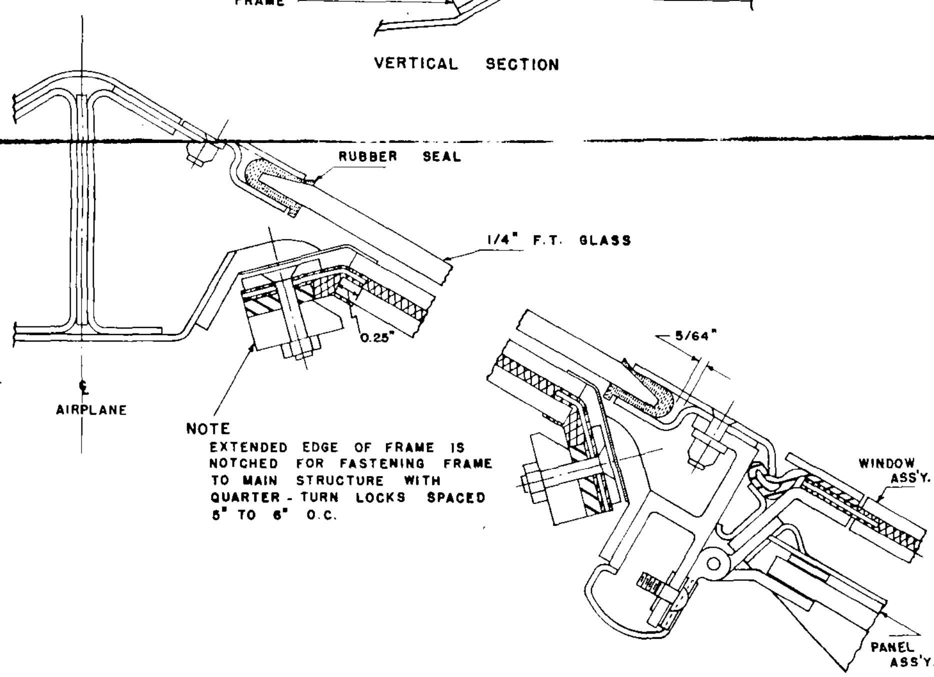
(2) A continuous type attachment of the frame to the structure is desirable, insofar as it may be accomplished and satisfy the requirement for rapid opening of the rear windshield pane. Such continuous attachments permit direct and uniform transmission of loads from the panel into the structure. The use of a hinge arrangement for this purpose provides uniform load distribution, and rotation of the hinges tends to maintain a direct tensile stress in the plastic edge of the pane and to minimize shear failure.

(3) Attachment of the ends of the frame to the end posts usually is necessary, although such attachment may reduce the ease of opening the panel. If no end attachment is used, very heavy reinforcement of the ends of the frame is required to provide sufficient stiffness for preventing the bird from bending the end of the panel and entering the cockpit.

(4) The upper and outboard edges of the windshield panel, over which the bird carcass tends to slide on leaving the panel, should be arranged so that any wedging action of the carcass will not



VERTICAL SECTION



HORIZONTAL SECTION

ADDITIONAL REINFORCING:

REAR PANEL CORNER GUSSET ATTACHMENT TO FRAME STRENGTHENED.
OUTBOARD FRAME AND OUTBOARD HALF OF TOP AND BOTTOM FRAME OF REAR PANEL REINFORCED.

POINT OF FAILURE:

CORNER GUSSETS AND FRAME OF REAR PANE.

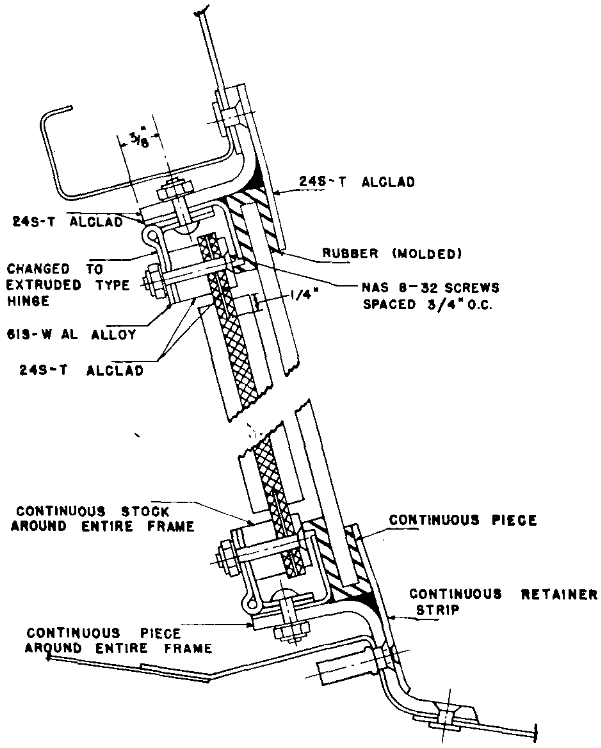
DOUGLAS DC-6

PENETRATION VELOCITY - M.P.H. 300
CARCASS WEIGHT - LBS. 4
TOTAL SLOPE - DEGREES 38 1/2
PANEL SIZE - IN. .... 15 X 28
PANE TEMPERATURE - °F. 80
THICKNESS OF POLYVINYL BUTYRAL - IN. 3/16

S.T. - SEMI-TEMPERED F.T. - FULL TEMPERED

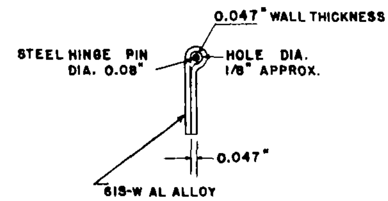
COCKPIT SECTION SUBMITTED FOR TEST AUG. 1946

Fig. 24 Section Details and Impact Test Data of Douglas DC-6 Windshield

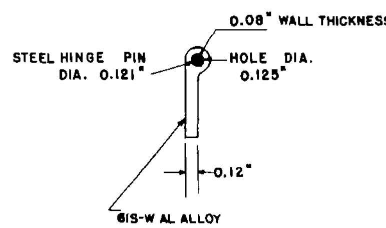


VERTICAL SECTION

ORIGINAL HINGE DESIGN



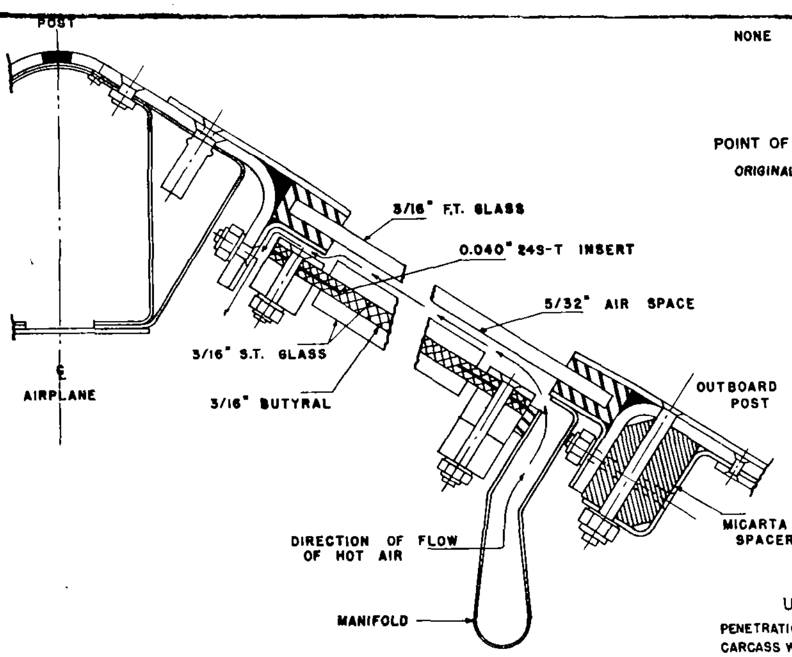
IMPROVED HINGE (EXTRUDED)



NONE

POINT OF FAILURE:

ORIGINAL HINGE FAILED.



HORIZONTAL SECTION

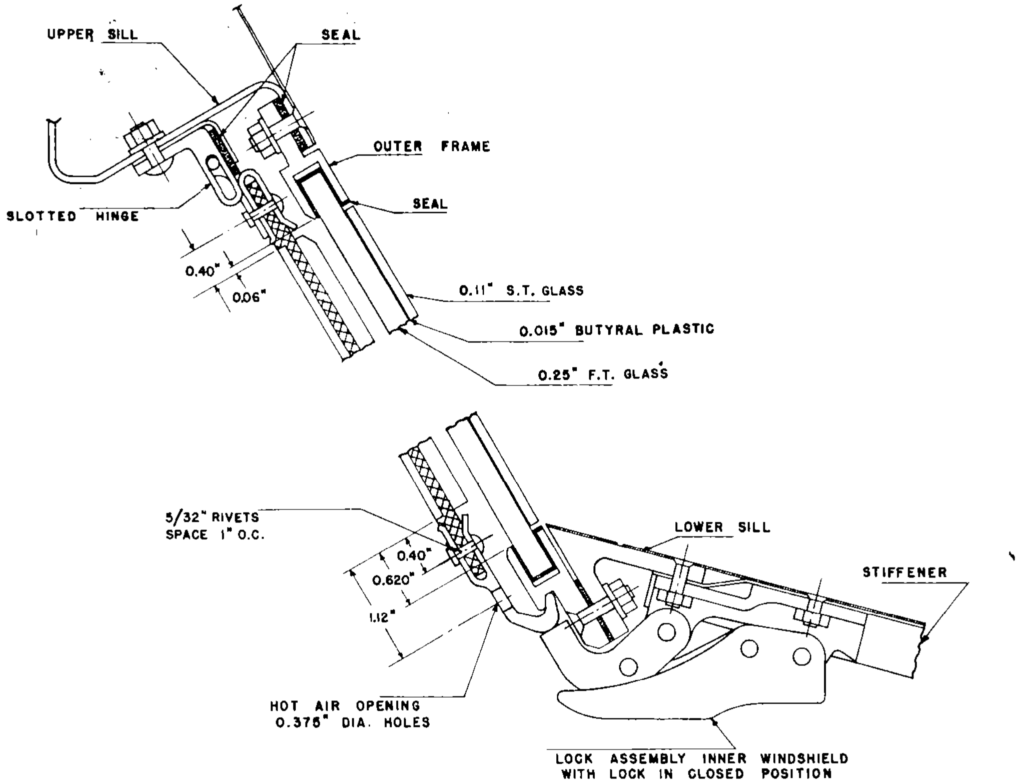
UNITED AIRLINES DC-4

PENETRATION VELOCITY-M.P.H.	250
CARCASS WEIGHT– LBS.	4
TOTAL SLOPE - DEGREES	41
PANEL SIZE– IN.	14 X 32
PANE TEMPERATURE– °F.	80
THICKNESS OF POLYVINYL BUTYRAL–IN.	3/16

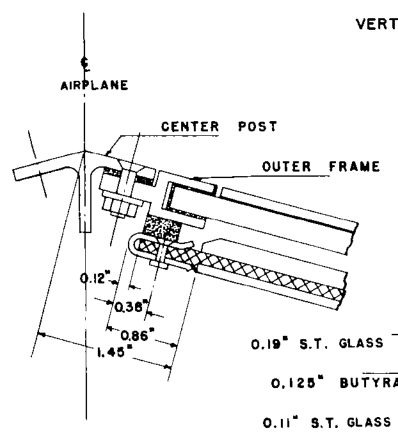
S.T.– SEMI-TEMPERED F.T.— FULL TEMPERED

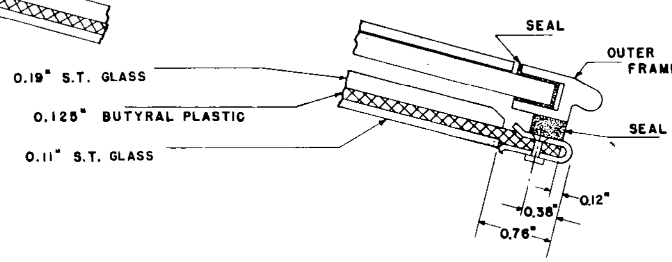
COCKPIT SECTION SUBMITTED FOR TEST NOV. 1946

Fig. 25 Section Details and Impact Test Data of United Airlines DC-4 Windshield



VERTICAL SECTION





ADDITIONAL REINFORCING:
NONE

HORIZONTAL SECTION

POINT OF WEAKNESS:

PRINCIPAL WEAKNESS OCCURRED AT EXTENDED EDGE OF PANE WHERE THE PLASTIC SHEARED AT THE RIVETS. THIS FAILURE WAS DUE TO THE LACK OF A METAL INSERT IN THE EDGE OF THE PANE.

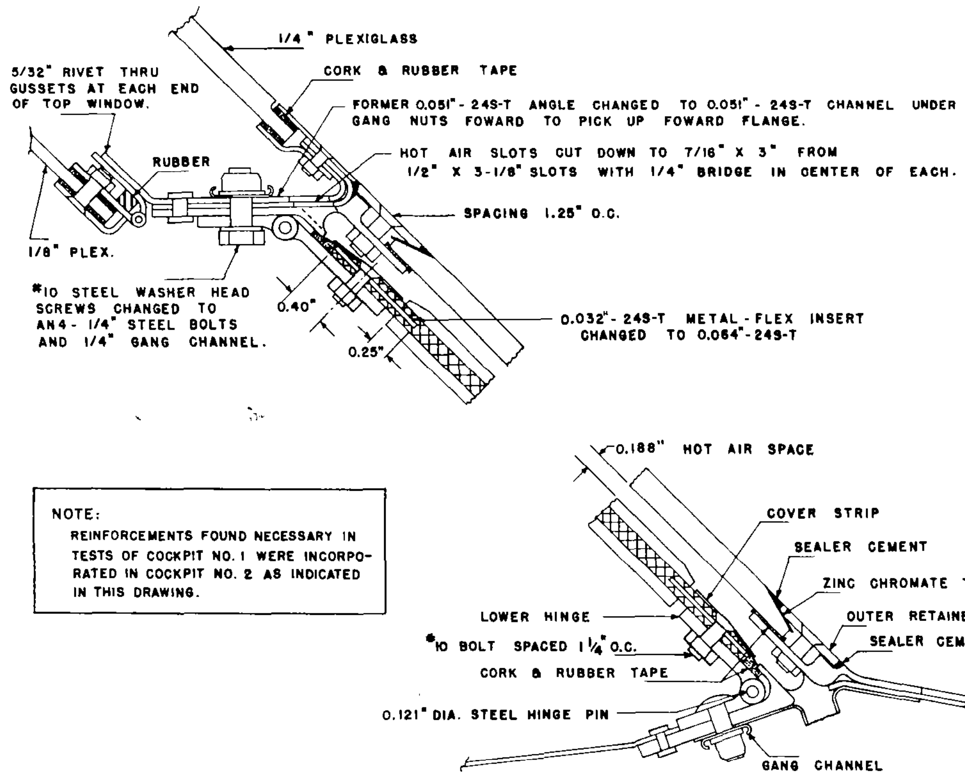
CURTISS-WRIGHT C46E

PENETRATION VELOCITY- M.P.H.	210
CARCASS WEIGHT- LBS.	4
TOTAL SLOPE- DEGREES	43
PANEL SIZE-IN.	13 X 24
PANE TEMPERATURE- °F.	80
THICKNESS OF POLYVINYL BUTYRAL-IN.	1/8

S.T.- SEMI-TEMPERED F.T.- FULL TEMPERED

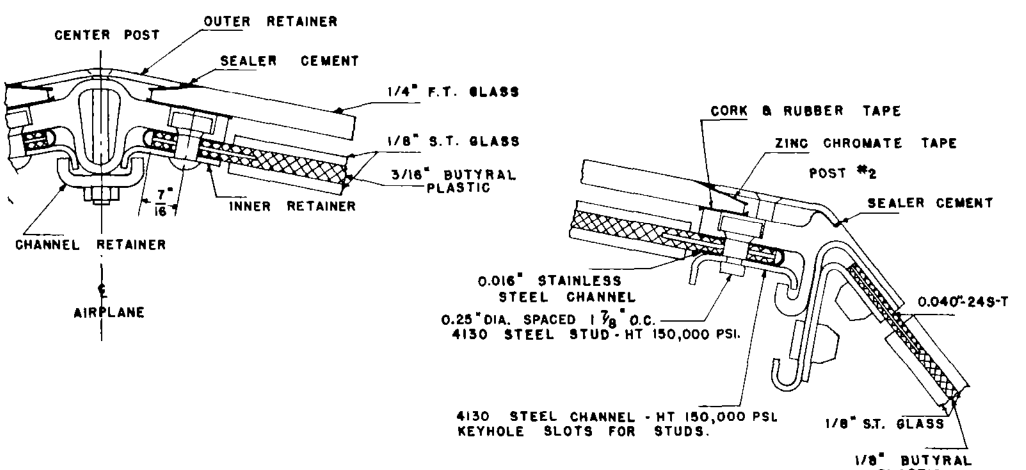
COCKPIT SECTION SUBMITTED FOR TEST SEPT. 1945

Fig. 26 Section Details and Impact Test Data of Curtiss-Wright C46E Windshield



NOTE:
REINFORCEMENTS FOUND NECESSARY IN TESTS OF COCKPIT NO. 1 WERE INCORPORATED IN COCKPIT NO. 2 AS INDICATED IN THIS DRAWING.

VERTICAL SECTION



HORIZONTAL SECTION

ADDITIONAL REINFORCING:

NO REINFORCEMENTS WERE USED IN COCKPIT NO. 2 .

POINT OF WEAKNESS:

SUPPORTING STRUCTURE BUCKLED WHEN POINT OF IMPACT OCCURRED NEAR TOP EDGE.

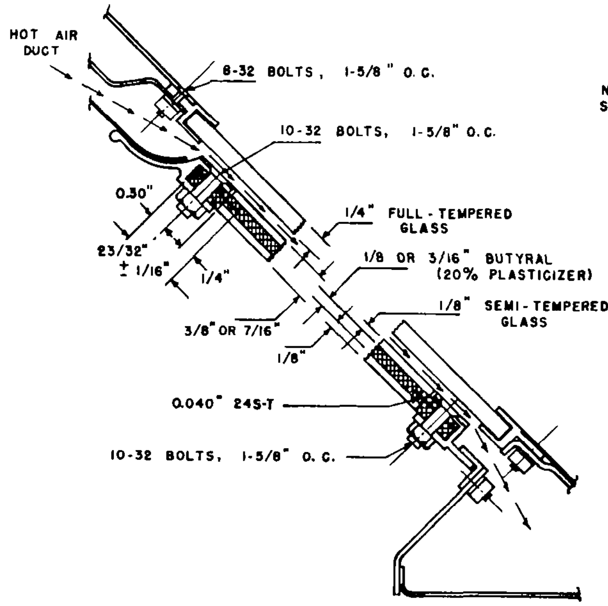
MARTIN MODEL 202

PENETRATION VELOCITY - M.P.H.	255
CARCASS WEIGHT - LBS.	4
TOTAL SLOPE - DEGREES	47
PANEL SIZE - IN.	14 X 24
PANE TEMPERATURE - °F.	60
THICKNESS OF POLYVINYL BUTYRAL - IN.	3/16

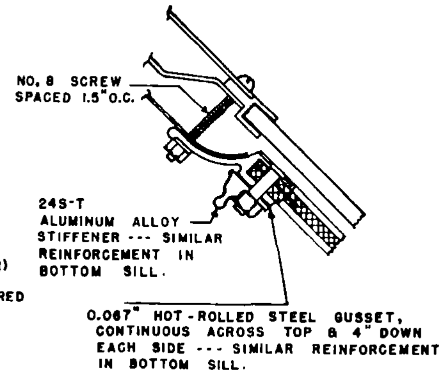
S.T. - SEMI-TEMPERED F.T. - FULL TEMPERED

COCKPIT SECTION SUBMITTED FOR TEST OCT. 1946

Fig. 27 Section Details and Impact Test Data of Martin Model 202 Windshield



VERTICAL SECTION OF MAIN WINDSHIELD PANEL



VERTICAL SECTION UPPER SILL

ADDITIONAL REINFORCING:

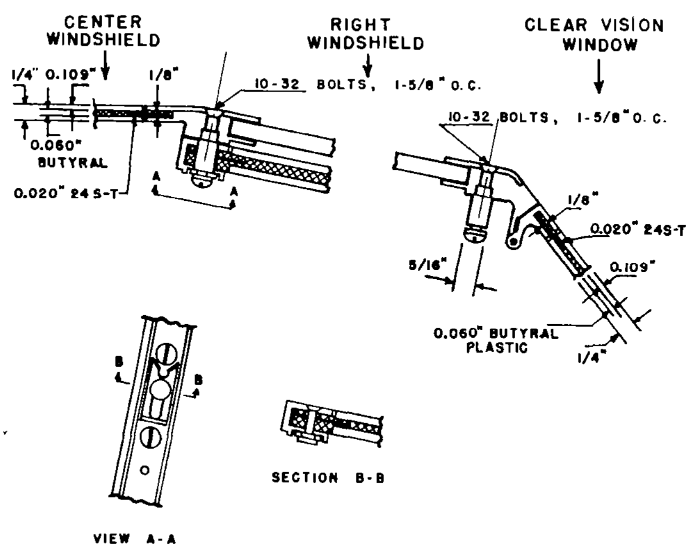
0.080 IN. X 2 IN. 24S-T EXTERNAL GUSSETS ADDED TO TOP AND BOTTOM OF ALL WINDSHIELD POSTS

POINTS OF FAILURE:

CORNER GUSSETS ON REAR PANE

HORIZONTAL FRAME MEMBER LACKED STIFFNESS

VERTICAL POSTS FAILED AT POINTS OF INTERSECTION WITH COCKPIT STRUCTURE



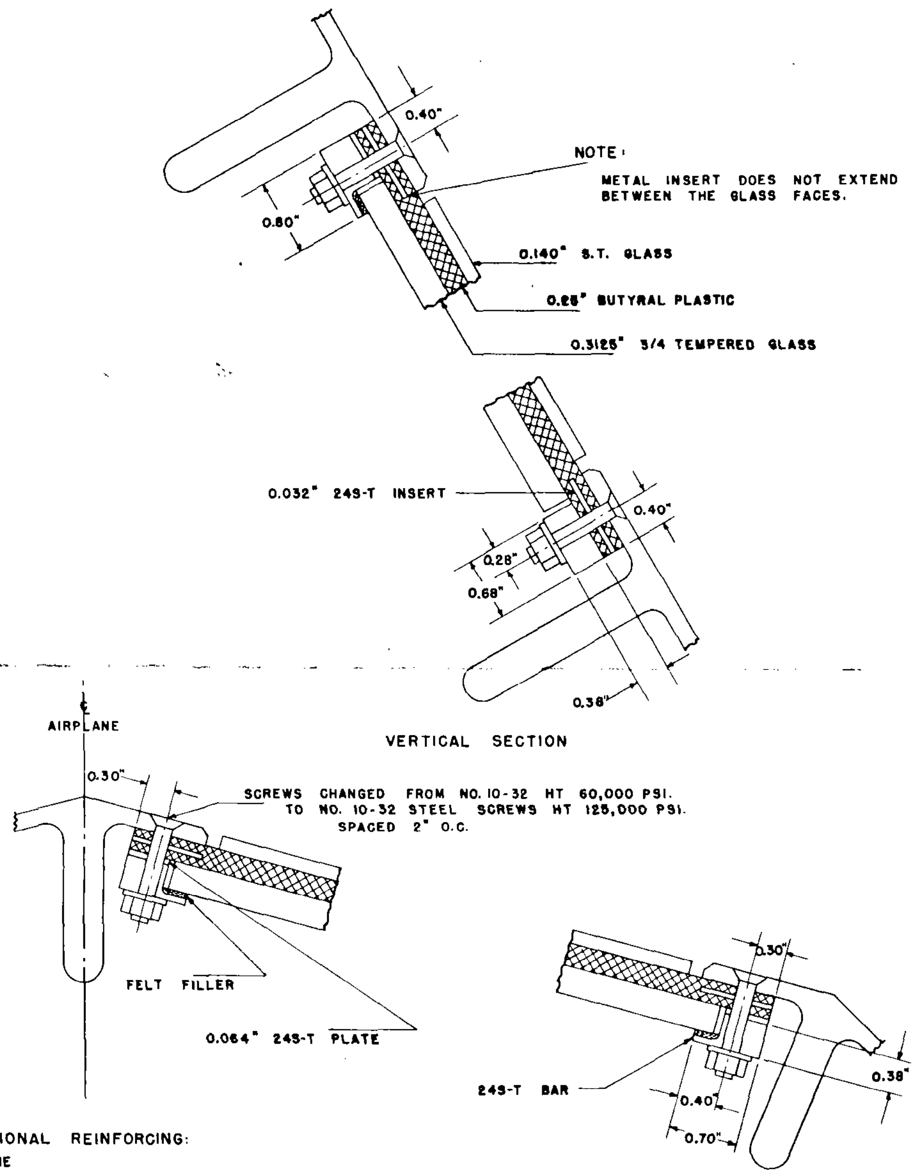
HORIZONTAL SECTION OF MAIN WINDSHIELD AND ADJACENT PANELS

BEECH MODEL 34

PENETRATION VELOCITY-MPH	220
CARCASS WEIGHT-LBS	4
TOTAL SLOPE-DEGREES	46
PANEL SIZE-IN.	17 X 18
PANE TEMPERATURE-°F.	80
THICKNESS OF POLYVINYL BUTYRAL-IN.	3/16

COCKPIT SECTION SUBMITTED FOR TEST APRIL 1947

Fig. 28 Section Details and Impact Test Data of Beech Model 34 Windshield



ADDITIONAL REINFORCING:

NONE

HORIZONTAL SECTION

POINT OF WEAKNESS:

LACK OF METAL INSERT THICKNESS CAUSED EXTENDED EDGE TO SHEAR AT THE BOLTS. LACK OF WIDTH OF METAL INSERT CAUSED PLASTIC TO SHEAR BETWEEN EDGE OF GLASS FACE AND FRAME.

BOEING MODEL 377

PENETRATION VELOCITY - M.P.H.	306
CARCASS WEIGHT - LBS.	4
TOTAL SLOPE - DEGREES	43
PANEL SIZE - IN.	20 X 20
PANE TEMPERATURE - °F.	80
THICKNESS OF POLYVINYL BUTYRAL - IN.	1/4

S.T. - SEMI - TEMPERED

COCKPIT SECTION SUBMITTED FOR TEST NOV. 1946

Fig. 29 Section Details and Impact Test Data of Boeing Model 377 Windshield cause failure of bolts or structural members carrying the principal impact load In many tests, wedging of the bird carcass along such edges has caused rotation of outside retainer strips and other members, and has resulted in twisting and failure of retaining bolts

(5) A variety of fast-action clamps, locks, and hooked lip arrangements for frame attachment have been tested, and are shown in Figs 24 to 29 Many such arrangements have proven satisfactory in practical installations It is required that such locking arrangements do not open as a result of impact loading, shock of impact, or reaction after shock

(d) Center V-posts, and other posts at the ends of or between windshield panes, usually will resist direct impact without serious failure if firm attachment of the post to the structure is made Light-weight riveted attachment fittings, with rivets in tension, have been found unsatisfactory

(e) After the bird carcass is deflected by the windshield panel, it tends to slide over the structure at the top or outboard edges of the panel, and cause structural buckling Maximum strength of panel attachment and frame in this region is required

(f) The use of a rigid type windshield panel with clamped edge mounting, such as a clamped full-tempered glass plate, results in large forces on the structure associated with the relatively small deformation of the panel These forces are directed principally to the rear and normal to the panel, and a rigid and uniform structure is required to transmit such loads

Application of some of these principles is shown in the practical installations of Figs 24 to 29 Also shown in these illustrations are the various frame, sill, and post component dimensions, bolt and rivet arrangement and sizes, and other details of construction, as well as the velocities at which panels mounted in these structures were tested, and the apparent points of initial structural failure

Although no complete and precise data have yet been obtained concerning the impact forces and the loads transmitted into the structure from the windshield panel, the foregoing information on structural sections, bolt sizes and spacings provides a general guide in this connection

Impact Resistance of Clear-Vision and Auxiliary Windows

Tests involving impact upon corner cockpit windows adjacent to the windshield, side windows, and auxiliary transparent panels above or below the main windshield panel, have been included in the present test program.

Although such panels are usually mounted at a large angle of slope to follow the curvature of the fuselage, and are not in a direct fore and aft line with the pilot, it has been found from numerous tests that failure of such panels offers serious hazard to the pilot In particular, it has been found that panels forward of the pilot and with appreciable frontal area may fail so that a part or all of the panel and frame, glass or plastic splinters, or portions of the bird, will be thrown in a direction approximately normal to the plane of the window and in the general direction of the pilot

Panels of this type which were tested included laminated safety glass with clamped edge support, laminated flexible bolted edge installations, and methyl methacrylate plastic panels Some of the installations tested are described in Tables I and II, which also show the corresponding test results

The results of impact tests upon such windows are generally similar to those obtained with identical panel materials and panel mounting methods in main windshield panels Panels with clamped edge mounting usually have low impact strength and, upon failure, tend to be pulled out of the mounting frame in one or several large pieces which may be thrown across the cockpit with considerable force Methyl methacrylate panels also are relatively weak, and fail by breaking into large fragments with sharp corners and edges Methyl methacrylate panels above the main windshield have been penetrated in some tests by the bird carcass sliding upward after direct impact upon the main windshield panel

The laminated flexible bolted edge type of panel installation has been shown, by the tests, to provide the maximum impact strength for auxiliary windows as well as for main windshield panels In general, the same relationships between penetration velocity and panel thickness, edge mounting, metal insert arrangement, panel temperature, and other details of panel construction and arrangement apply as already discussed in connection with the main windshield installation However, because of the usual small size of such windows in relation to normal windshield size, several impact characteristics which appeared in the larger panels are of especial importance in connection with the smaller panels

Because of the usual small size of such panels, bird impact upon the panel is close to all edges and results in high forces in the panel mounting and frame In addition, the small size of the pane results in a pocketing effect of the bird in the panel as the plastic undergoes stretching, which tends to neutralize the effect of the large angle of slope usually used for such windows The effect of impact upon small windows set at high angle of slope, therefore, is similar to the effects already discussed in connection with panel size and panel slope

It may be concluded that in the design of such windows only slight consideration should be given to the effect of an increase of slope over moderate angles of slope in determining butyral plastic interlayer thickness, if the forward area of the panel is appreciable. Also, no decrease in size or spacing of mounting bolts should be made beyond that required for a main windshield panel of moderate slope and similar plastic thickness

Tests of a variety of hinged clear-vision windows indicate the need for strong attachment, positive acting locks of high strength, and rigid frame to carry the panel edge forces to the points of attachment to the structure Failure of windows has commonly occurred through opening of the lock during impact, failure of portions of the lock, failure of the hinge or its attachment to the structure, or severe distortion of the window frame Insufficient systematic data have been obtained to permit specific conclusions concerning strength requirements for such frames, locks, and hinges

Optical Deviation Measurements

Optical deviation measurements were made upon certain of the panes used for impact tests Because of the relatively small number of optical tests carried out, and as no selection of panes was made for such tests, the results are not completely representative of the optical characteristics which might be obtained in commercial production

(a) Measurement with Plate Glass

Tests were made of optical deviations produced by full-tempered glass plates from 0 25 to 1 25-in thickness The tests indicate much better optical qualities than those found in butyral plastic laminated panes The maximum deviation indicated by any of the panes included in the tests was two minutes of arc The maximum rate of change was approximately 0 25 minutes of arc per inch No correlation was found to exist between thickness of full-tempered glass and amount of deviation of line of sight.

(b) Measurements with Laminated Panes

Optical deviation measurements were made upon various laminated panes with different thickness combinations of surface glass and butyral plastic interlayer Some results in this connection are shown in Fig 30 These show that the proportion to the total panel area of the area with less than three minutes of arc deviation will increase as the ratio of glass thickness to plastic interlayer thickness increases

With the total glass thickness twice as great as the plastic thickness, or with the thickness of each glass face equal to that of the plastic interlayer, approximately 50 per cent of the total panel area has optical deviation values less than three minutes If the total glass thickness is equal to the thickness of the butyral plastic, only about 25 per cent of the total panel area shows optical deviation less than three minutes

In Fig. 31 is shown a typical optical deviation photograph of a glass plastic laminated type windshield pane consisting of 0.25-in butyral plastic interlayer and 0 188-in. full-tempered glass faces The center area of the pane is relatively free from deviation of line of sight, however, at the edges the amount of optical deviation increases in a characteristic manner Usually this relatively high optical deviation associated with the edges of the pane is limited to a border area of one to two inches around the pane

SPECIAL PROBLEMS ASSOCIATED WITH IMPACT RESISTANT WINDSHIELD DESIGN

In addition to the specific data given in previous sections of this report, certain observations were made which relate to design problems associated with impact-resistant windshields These observations are con-

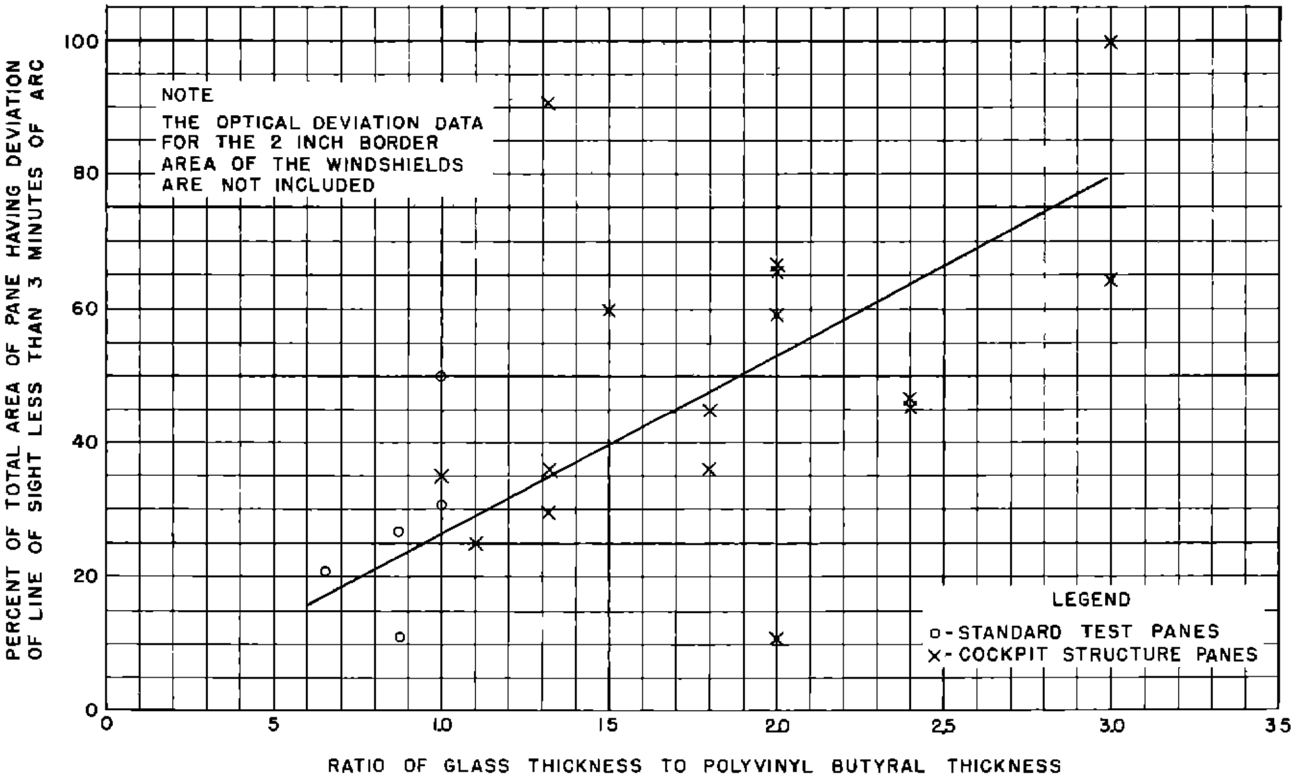


Fig 30 Variation of Deviation of Perpendicular Line of Sight With Glass-Plastic Thickness Ratio of Laminated Panes

cerned with thermal and splintering characteristics of windshield panels

Thermal Characteristics

Several independent but closely related problems concerned with thermal characteristics of windshield panels are encountered in practical aircraft applications These problems involve the heat transmission characteristics, and the variation of panel impact strength with temperature as previously discussed

The heat transmission characteristics, concerned with the provision of adequate heat on the outer face of the windshield panel for de-icing purposes and the minimization of heat radiated from the inner face of the windshield because of possible pilot discomfort, are related to the windshield impact characteristics principally through the effect of the location and thickness of the polyvinyl butyral or other plastic

It is necessary to minimize use of butyral plastic between the source of heat in the windshield and the front face of the panel, because of the relatively low heat transmission of plastic as compared to glass For the same reason, the use of thick plastic layers behind the source of heat is advantageous

The maintenance of a reasonably uniform temperature of the desired magnitude in the butyral plastic interlayer of a windshield panel in a practical aircraft installation is a difficult problem However, as indicated in previous discussion, such temperature control is required to insure maximum impact strength In the approximate temperature range from 80° to 140° F, the butyral plastic with 20 per cent plasticizer exhibits good energy absorbing characteristics, but outside of this range the ability to absorb energy of bird impact decreases rapidly

Heat for maintenance of adequate plastic temperature in the windshield panel is readily available in windshield installations where heat de-icing is used Warm air circulated through a double pane arrangement, as commonly used for de-icing, provides sufficient heat for maintaining the plastic temperatures necessary for high strength Partial

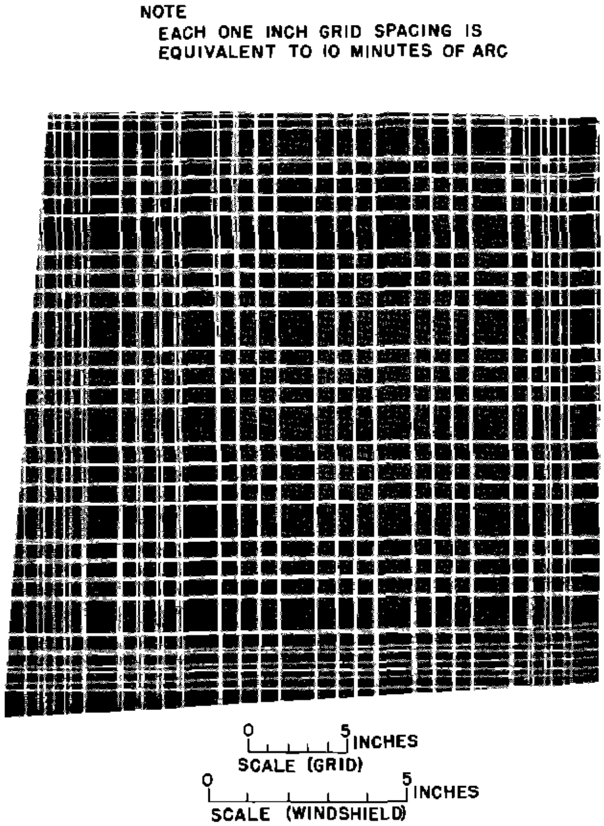


Fig 31 Typical Optical Deviation Photograph of Windshield Pane With 0 25-in Polyvinyl Butyral Interlayer and 0 188-in. Semi-Tempered Glass Faces

application of such warm air has been used in practical installations for this purpose

The use of warm de-icing air provides an uneven temperature distribution across the panel For example, the heated air may enter the inboard end of the panel at a temperature of 200° F or higher and leave the outboard end of the panel at 100° to 125° F The plastic temperature at the two ends of the panel will vary by similar large amounts Impact tests have been made with such temperature conditions existing, and it was found that the impact strength and type and location of failure are such as would be expected from application of the data shown in Fig 14 to different portions of the panel Consideration should be given in practical design to the panel strength existent with such a temperature distribution, and with either total or partial heat applied Further consideration should be given to the location of areas of minimum strength, and every effort made to obtain maximum strength at portions of the panel area which are particularly critical

The use of electrically heated panes, incorporating conductive coatings, appears well suited to maintaining suitable plastic temperature for maximum strength In such installations, the temperatures at different portions of the heated pane are more uniform than in panels using hot air for heating, and the magnitude of the temperature can be brought to any reasonable desired value by variation of the applied voltage From the strength standpoint, such panes appear to possess definite advantages

Splintering of Glass and Plastic Panels

In addition to the hazard associated with penetration of a windshield panel, by a colliding bird which enters the cockpit with considerable residual velocity, a hazard exists from splinters or larger sharp-edged pieces of glass or plastic resulting from the impact A photograph of glass splinters thrown off the rear surface of a laminated pane during impact is shown in Fig 32 Broken particles are produced by the impact with all types of glass used for the rear surface of the pane, even though no penetration of the pane by the carcass occurs.

The laminated glass-butyral plastic pane possesses serious splintering characteristics At impact velocities greater than that required to crack the glass faces, but considerably lower than that required for panel penetration, splinters are thrown from the rear pane face These splinters are small in size and travel at a velocity of the order of 500 feet per second as estimated from high speed photographs

Various objects have been set up behind panels of this type to obtain an indication of the penetrating power of the glass splinters in soft wood, cardboard, and putty-like materials It has been found that a small proportion of the splinters will stick in the surface of soft wood or cardboard, and that a large number of splinters will penetrate the surface of the putty The splinters will not break thin glass such as used in eye-glasses or goggles

Several possibilities for controlling the projection of splinters from the rear face of the laminated pane into the cockpit were investigated Two methods were tried

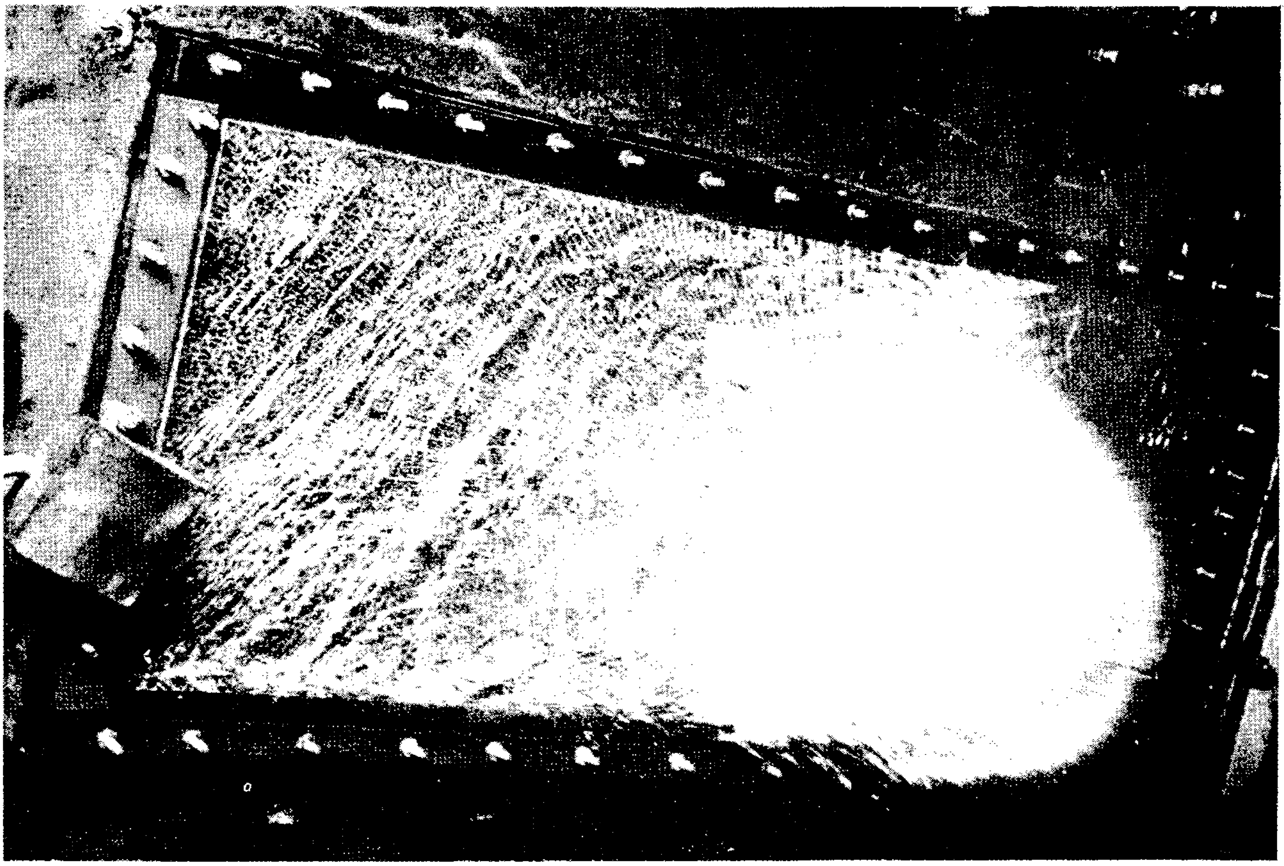


Fig. 32 High Speed Photograph of Splintering of Glass-Plastic Pane at Time of Impact

(1) utilizing a relatively hard plastic in place of glass on the rear face of the laminated pane.

(2) suspending a thin sheet of hard plastic a short distance behind the standard glass-plastic laminated pane.

The first method is illustrated in Table IV by Type Nos. 401.2 and 401.4, where the butyral plastic interlayer was laminated with methyl methacrylate plastic. Impact tests indicate that the strength of such a pane is lower than a similar pane using tempered glass faces. Cracks developing in the methyl methacrylate plastic faces of the panel appear to be transmitted to the butyral plastic interlayer, thereby lowering its strength.

Using a glass front face and methyl methacrylate plastic rear face for the pane, as shown in Table IV, Type No. 402.3, introduces a problem of unequal coefficients of thermal expansion for the two materials, which results in bending of the pane and consequent optical distortion.

In the case of the No. 402.3 pane, a comparatively thin layer of methyl methacrylate plastic is employed for the rear face. Outstanding practical disadvantages of this construction are poor optical characteristics and low scratch resistance of the plastic surface. No other plastics were considered as suitable for this purpose at the time of this investigation.

The second method of solution of this problem consisted of suspending a methyl methacrylate plastic sheet of 0.080-in. thickness behind the main panel to stop the splinters. It was found that a thin pane suspended in this manner is broken by impact as a result of the large distortion of the plastic interlayer in the main panel. Further, this added pane possesses undesirable optical characteristics, disturbing reflections from the added surfaces, and low scratch resistance.

Laminated glass-butyral plastic panes in which the rear glass face consisted of annealed glass and full-tempered glass were tested as well as the semi-tempered glass normally used No large variation in the amount of fine splinters produced by the different types of glass was observed

ADDITIONAL STUDIES REQUIRED

Several phases of the present development program require additional study and investigation These may be summarized as follows

1 Study of variation of impact strength with temperature for various butyral plastic thicknesses and for various butyral plastic plasticizer contents Related to this is the study of means for extending impact resistance of butyral plastic over a greater temperature range

2 Investigation of effect of variation of the mass of the bird carcass

3 Study to determine effect of size, shape, and slope of the panel upon impact strength

4 Determination of magnitude of the impact forces involved and the energy absorbed by various windshield panel designs and arrangements

5 Study of additional methods of overcoming the problem of glass splintering from the glass-butyral plastic laminated type pane

6 Investigation of methods for measuring and improving optical deviation and light transmission characteristics of glass-butyral plastic windshields with both flat and curved panels

7 Securing of more complete data on detailed design of edge mounting arrangements

8 Investigation of possibility of replacing present method of testing windshields with method of design analysis in order to simplify determination of compliance of windshield structures with Civil Air Regulations

CONCLUSIONS

1 The general type of panel construction which provides the greatest strength, when compared upon the basis of equal weight with other panel types, is the type utilizing a laminated glass-plastic type pane with thick polyvinyl butyral plastic interlayer, and with the extended flexible plastic edges bolted to the frame structure

2 The resistance of a windshield panel to impact with a bird carcass, as measured by the velocity of carcass required to cause penetration, varies approximately as the logarithm of the pane thickness However, in the laminated glass-plastic type pane with extended plastic edge, the thickness of the glass has little effect on impact strength within reasonable limits The impact strength of this type of pane is determined principally by the thickness of the butyral plastic interlayer

3 An optimum temperature and plasticizer content exist for maximum impact strength of all panes in which plastic materials contribute appreciably to the strength Polyvinyl butyral plastic with 20 per cent plasticizer content, as commonly used, exhibits greatest energy absorbing characteristics in the approximate temperature range from 80° to 140° F

4 In a double-pane windshield arrangement, where a relatively thin front glass with good thermal transmission characteristics is used, the front pane contributes little to the impact strength of the combination

5 The angle of impact upon the windshield panel has great effect upon its impact strength It is indicated that the impact strength, as measured by the carcass velocity required for penetration, varies approximately as the secant of the total angle of panel slope

6 Impact upon the windshield panel is most severe for locations close to the aft edges or rear upper corner of the panel

7 Size and shape of windshield panel have little effect upon impact strength over a considerable range commonly used in aircraft practice

8 The general rigidity and energy absorbing characteristics of the windshield supporting structure have considerable effect upon the strength exhibited by the windshield panel A structure which is highly elastic, or which undergoes buckling, apparently causes lower forces to develop in the panel with less tendency for panel failure Uniformity of structural rigidity around the panel also appears advantageous

9 Apparently no advantage exists in utilizing heavy rigid posts at the ends of the windshield panel or between panels, except to reduce glass cracking in panels adjacent to the panel upon which impact occurs

10 Common types of failure, occurring separately or in combination in the glass-butyral plastic type of windshield installation

having extended plastic edges bolted to the cockpit frame structure, are as follows

(1) Shearing of extended plastic edge of pane at bolts
(2) Shearing of pane at inner edge of the metal strip inserted in the extended plastic edge
(3) Failure in the main body of the pane, usually in the form of a tear in the plastic interlayer
(4) Failure or severe bending of the immediate windshield frame
(5) Failure in shear or tension of the panel mounting bolts
(6) Failure in the hinge, clamp, or bolt attachment of the windshield frame to the sills and posts
(7) Failure of the sills or posts, or their attachment to the aircraft structure

11 Normal deflection of the bird carcass by the windshield to the upper outboard corner of the panel, to follow the direction of panel slope, demands particular attention with regard to attachment of the panel and frame in this region

12 The use of a rigid type windshield panel with clamped edge mounting, such as a full-tempered glass plate, results in large forces on the structure associated with the comparatively small deformation of the pane A rigid and uniform structure is required to transmit such loads

13 The laminated flexible bolted edge type of glass-plastic panel installation provides maximum impact strength for auxiliary windows Because of pocketing effects of the carcass in small panels of this type, the helpful effect of normal large angles of slope tends to be negated, and butyral plastic thickness and frame supporting strength equivalent to the main windshield panel is usually required

14 The optical properties of the glass-plastic laminated panes, measured in terms of optical deviation of line of sight, varies with the ratio of glass to butyral plastic thickness It is indicated that the thickness of each glass face should be equal to the thickness of the plastic interlayer to obtain normally acceptable optical characteristics

15 The glass-butyral plastic laminated type windshield pane possesses undesirable splintering characteristics Tempered or annealed glass produces large quantities of high velocity splinters The use of methyl methacrylate plastic, or other similar hard plastics on the rear face of the pane, greatly reduces splintering but produces undesirable optical characteristics

16 It is indicated that in laminated type panes the ratio of thickness of 24S-T aluminum alloy metal insert in the plastic pane edge to the thickness of the butyral plastic interlayer should be between one-sixth and one-fourth, for thickness of plastic interlayer 0 188-in or less and one-fifth to one-third for thickness of plastic interlayer greater than 0 188 in

17 The panel mounting bolts should be spaced at least two bolt diameters from the edge of the pane The bolt size and distance between bolts should provide strength equivalent to a 2-in spacing of No 10 steel bolts (100,000 psi H T) for 0 125 in butyral plastic interlayer thickness, and a 1-in spacing of identical bolts for a 0 25-in interlayer thickness In general, small bolts at close spacing provide more uniform support than large bolts at wide spacing