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RESEARCH MEMORANDUM

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STRUCTURAL VULNERABILITY OF THE BOEING B-29 AIRCRAFT
 WING TO DAMAGE BY WARHEAD FRAGMENTS

By Eldon E. Kordes and William J. O'Sullivan, Jr.

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RESEARCH MEMORANDUM

STRUCTURAL VULNERABILITY OF THE BOEING B-29 AIRCRAFT

WING TO DAMAGE BY WARHEAD FRAGMENTS

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SUMMARY

An elementary type of analysis has been used to determine the amount of wing tip that must be severed to produce irrevocable loss of control of a B-29 airplane. The remaining inboard structure of the Boeing B-29 wing has then been analyzed and curves are presented for the estimated reduction in structural strength due to four general types of damage produced by rod-type warhead fragments. The curves indicate the extent of structural damage required to produce a kill of the aircraft within 10 seconds.

INTRODUCTION

In the problem of defense against attacking bomber aircraft, it is desirable that the elimination of the bomber as a threat be accomplished quickly and be evident promptly after defensive action is undertaken in order to minimize the expenditure of anti-aircraft weapons. Failure to destroy the aircraft quickly increases the radar tracking time and thus results in a defensive system that may be saturated by a mass bomber attack so that defensive ability is lost. The employment of warheads producing large fragments, such as the rod type, capable of inflicting severe structural damage to bomber aircraft may afford the desired quick kill detectable by radar tracking.

The vulnerability of bomber aircraft to gunfire, blasts, and rockets has been investigated experimentally and reported in references 1 to 4. Not all these experimental results, however, can be extrapolated to assess the effectiveness of large fragments, such as the rod type. The objective of this report is the determination of the reduction in structural strength produced by narrow cuts of various lengths in the wing structure of a Boeing B-29 bomber and the determination of the structural members that must be severed to produce a quick structural kill. The problem of evaluating the vulnerability of the Boeing B-29 bomber to a quick structural

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kill is herein considered resolvable into two parts: first, determination of the minimum aerodynamic damage that must be inflicted to produce irrevocable loss of control; second, determination of the severity of structural damage required to cause structural failure in order to produce the minimum or greater aerodynamic damage. The severity of structural damage has been evaluated in terms of the length of cut in the structure and the structural members that are severed.

SYMBOLS

b	undamaged wing span, ft
$C_{l\delta}$	rolling-moment coefficient of one aileron per unit of aileron deflection, 1/deg
c	chord of box beam, ft
c_{av}	average chord of box beam, ft
I	section moment of inertia, in. ⁴
L	effective length of cut, ft
L_1	lift of one-half of undamaged wing, lb
L_2	lift on damaged half of wing after severance of tip and before restitution of total wing lift to its original value, lb
l_1	distance from plane of symmetry to center of lift of one-half of undamaged wing, ft
l_2	distance from plane of symmetry to center of lift of damaged half of wing after severance of wing tip, ft
M	bending moment, lb-in.
P	load, lb
q	dynamic pressure, lb/sq ft
S	area of undamaged wing, sq ft
T	torque, lb-in.

t	skin thickness, in.
y_1	distance from plane of symmetry to tip of undamaged wing, ft
y_2	distance from plane of symmetry to tip of damaged wing, ft
δ_a	aileron deflection, deg
σ	stress, lb/sq in.
τ	shear stress, lb/sq in.

AERODYNAMIC ESTIMATES

The minimum aerodynamic damage corresponding to tracking radar evidence of kill of the bomber is considered to be that which just produces irrevocable loss of control. It is assumed that in order to establish evidence of loss of control the radar will continue to track the bomber for a period of about 10 seconds after warhead explosion. The period of 10 seconds is considered to be adequate for the aerodynamic damage to be treated on the basis of static stability rather than necessitating dynamic-stability considerations. It is recognized that severance of a wing tip by fragments from a warhead leaves the damaged wing with a tip that is probably very ragged. This condition precludes the possibility of all but the crudest of aerodynamic calculations and therefore justifies the approximations employed in the following estimations.

Selection of flight condition.- It is presumed that defensive action against the approaching bomber is capable of being undertaken at a range such that the bomber has not yet entered into the over-target bombing run. Accordingly, the bomber is assumed to be flying at maximum airspeed in order to minimize the time that it is within reach of antiaircraft fire. The airspeed operational limits employed in the aerodynamic and structural design of the subsonic B-29 airplane are specified in terms of equivalent airspeed; thus, the need for assumption of an altitude of the approaching bomber is eliminated. The assumed weight of the bomber is that of full bomb load and partial fuel load. This choice of loading results in a realistic flight condition for the bomber approaching the target area and this condition is approximated by design condition E, positive low angle of attack, of reference 5, for which condition the equivalent airspeed is 345 miles per hour and the gross weight is 103,000 pounds.

Rolling moment produced by loss of wing tip.- A wing panel is considered in the aerodynamic estimates to consist of all wing plan-form area lying to one side of the plane of symmetry, including the aileron and the

area blanketed by the fuselage and nacelles, as shown in figure 1. Severance of one wing tip is assumed to produce on the damaged wing panel a spanwise contraction of the lift distribution without altering the spanwise lift distribution of the undamaged wing panel. The contraction is assumed to be such that the local lift per unit of span at any given fraction of the span of the damaged panel is equal to the local lift per unit of span at the same fraction of the span of the undamaged panel. The span, lateral center of lift, and lift of the damaged wing panel before and after severance of the tip are then related by

$$\frac{y_2}{y_1} = \frac{l_2}{l_1} = \frac{L_2}{L_1} \quad (1)$$

The total lift of the damaged wing is then

$$L_1 + L_2 = L_1 \left(1 + \frac{y_2}{y_1} \right)$$

and its rolling moment is

$$L_1 l_1 - L_2 l_2 = L_1 l_1 \left[1 - \left(\frac{y_2}{y_1} \right)^2 \right]$$

It is next assumed that, by an increase of the angle of attack, the lift of the damaged wing is restored to that carried by the wing before severance of the tip. The factor by which the lift is increased is then

$$\frac{2L_1}{L_1 + L_2} = \frac{2}{1 + \frac{y_2}{y_1}}$$

When it is assumed that restoration of lift does not further alter the lateral center of lift on each wing panel, the damaged-wing rolling moment is increased by this same factor so that the rolling moment of the damaged wing with restored lift is

$$2L_1 l_1 \frac{1 - \left(\frac{y_2}{y_1}\right)^2}{1 + \frac{y_2}{y_1}}$$

For the assumed flight conditions, the term $2L_1$ is the weight of the airplane which is 103,000 pounds, and the location of the lateral center of lift l_1 is found from reference 5 to be 30.6 feet. The rolling moment of the damaged wing in pound-feet is then

$$3,151,800 \frac{1 - \left(\frac{y_2}{y_1}\right)^2}{1 + \frac{y_2}{y_1}} \quad (2)$$

Restoring moment produced by ailerons.- It is tentatively assumed, and later verified, that the amount of wing tip that must be severed from one wing panel before irrecoverable loss of lateral control is incurred is sufficient to include the entire aileron of the damaged wing panel. Accordingly, it is assumed that the available aileron restoring moment is that produced by the one remaining aileron when fully deflected. The rolling moment produced by one aileron can be written as

$$qSbC_{l_\delta} \delta_a \quad (3)$$

From unpublished measurements of abrupt aileron rolls performed with a B-29 airplane and calculated values of wing damping-moment coefficient in roll obtained by the method of reference 6, the value of C_{l_δ} for one aileron is estimated to be 0.000818. For the assumed flight condition and full aileron deflection of 17.5° , the restoring rolling moment obtainable from one aileron is calculated to be 1,055,000 pound-feet. Attainment of this aileron rolling moment is contingent upon severance of the wing tip without jamming or destruction of the aileron actuating mechanism of the remaining aileron, and the existence of control forces on the remaining aileron that are within the physical capabilities of the pilot. Each aileron is actuated by a separate control cable. The ailerons are individually trimmed to float in neutral position in the event of severance of the actuating cables. Unpublished flight tests

indicate that under the assumed flight conditions the control force produced by full deflection of one aileron is well within the physical capabilities of the pilot. Attainment of the above aileron rolling moment is thus practical.

Restoring moment produced by dihedral effect.- By deflection of the rudder the airplane can be yawed and a restoring rolling moment achieved from the dihedral effect. The attainable rudder deflection and the dihedral rolling moment in terms of an equivalent aileron deflection can be estimated from unpublished measurements obtained in steady sideslips with a B-29 airplane. From these measurements it is estimated that for the undamaged airplane under the assumed flight conditions the rudder force per unit rudder deflection is about 90 pounds per degree, the rudder force per unit sideslip angle is about 180 pounds per degree, and the equivalent aileron deflection of a single operable aileron per unit of sideslip angle is about 2.0° per degree. From measurements of control forces applied by pilots it is reasonable to assume that a pilot can apply for a period of 10 seconds a rudder force of 300 pounds. When aid of the copilot is assumed, the total applied rudder force is taken as 600 pounds so that a rudder deflection of 6.66° results. It is thus evident that the amount of dihedral rolling moment that can be produced is limited by the rudder control forces rather than by the available rudder deflection which is about 17° . The angle of sideslip produced by 600 pounds rudder force is about 3.33° , and the equivalent deflection of a single aileron is about 6.66° . For the assumed flight condition the dihedral restoring moment for the undamaged airplane is then computed by formula (3) to be 401,500 pound feet.

The dihedral restoring moment of the damaged airplane with severed wing tip may be approximated in the following manner: For an airplane like the B-29 having constant dihedral angle along the wing span, the spanwise lift distribution produced by the dihedral effect is theoretically equivalent to a positive change of incidence of one wing panel and an equal and opposite change of incidence of the opposite wing panel. Accordingly, the dihedral rolling moment of the undamaged airplane may be written as

$$\Delta L_1 l_1 + \Delta L_1 l_1 = 2 \Delta L_1 l_1$$

and that of the airplane with severed wing tip as

$$\Delta L_1 l_1 + \Delta L_2 l_2$$

so that the ratio of the dihedral rolling moments of the damaged and undamaged airplanes is

$$\frac{\Delta L_1 l_1 + \Delta L_2 l_2}{2 \Delta L_1 l_1}$$

In accordance with the assumption of equation (1),

$$\frac{y_2}{y_1} = \frac{l_2}{l_1} = \frac{\Delta L_2}{\Delta L_1}$$

from which by substitution the ratio of the dihedral moments becomes

$$\frac{1 + \left(\frac{y_2}{y_1}\right)^2}{2}$$

The approximate restoring rolling moment attainable on the damaged airplane as a function of amount of severed wing tip is then

$$401,500 \left[\frac{1 + \left(\frac{y_2}{y_1}\right)^2}{2} \right] \quad (4)$$

Amount of severed wing tip producing irrevocable loss of control.- Equating the rolling moment produced by severance of a wing tip to the restoring moment attainable by full deflection of the remaining aileron and the attainable restoring dihedral moment yields for the assumed flight condition the amount of wing tip that must be severed before there ensues irrevocable loss of control, or

$$3,151,800 \frac{1 - \left(\frac{y_2}{y_1}\right)^2}{1 + \frac{y_2}{y_1}} = 1,055,000 + 401,500 \frac{1 + \left(\frac{y_2}{y_1}\right)^2}{2}$$

Therefore $\frac{y_2}{y_1} = 0.58$. The B-29 airplane semispan is 850 inches. The outboardmost point of severance producing irrevocable loss of control is then 493 inches from the plane of symmetry, or about 17 inches inboard of the inboard end of the aileron.

STRUCTURAL ESTIMATES

The primary wing structure of the B-29 is a two-spar box with light cover skin reinforced with large hat-type stiffeners. The lower spar caps on both the front and rear spars contribute as much as one-third of the tension-carrying material on the inboard wing panel (station 0 to 510) because of the wheel-well cutout and the fuel cell access panels. The wing leading and trailing edges contribute very little to the strength of the wing and hence are not considered in the estimates for the reduction in structural strength due to cuts made by warhead fragments.

Since the aerodynamic estimates indicate that it is possible for the B-29 airplane to fly with the outboard 42 percent of the span of one-half of the wing removed, only the inboard panel from station 0 to 510 is evaluated for reduction in structural strength.

In a study of this type, the infinite number of possible combinations of rod size, length, orientation, relative position of warhead at time of blast, path of fragments through the structure and possible additive effects of several cuts makes the problem of a complete structural analysis for all combinations practically impossible. Thus the following simplifying assumptions have been made and in view of the over-all uncertainties they are believed to be justified.

Assumptions.- The assumptions are as follows:

(1) The inner-wing panel (station 0 to 510) is divided into four bays that are approximately constant in structural configuration and/or net wing loading. The extent of each bay is shown in figure 1 and the net wing loading of l_g for design condition E, positive low angle of attack, (see ref. 5) is given in figure 2. The bays are designated

(a) Station 42 to 136. This bay extends from the fuselage junction to the wheel-well cutout.

(b) Station 136 to 202. This bay includes the wheel-well cutout and the inboard engine mount.

(c) Station 202 to 370. This bay extends from outboard of the wheel well to the outboard engine.

(d) Station 370 to 510. This bay extends from the outboard engine to the inboard end of the aileron.

(2) The structural stability under combined loads must be considered as well as the member stress developed after damage.

(3) The rod fragments are assumed to originate at infinity and to be capable of cutting completely through any member or members of the primary wing structure. The path of the fragment is taken to be perpendicular to the plane of the wing.

(4) All estimates of the reduction in structural strength are based on single rods of various lengths each cutting the undamaged wing.

(5) All cuts that are parallel to the wing spars are considered to inflict zero damage to the primary wing structure unless a rib is cut.

(6) The chordwise position of the cut between spars is assumed to be unimportant; only the amount of stressed material removed is of primary importance.

(7) If the cut does not include a rib or spar, the extent of damage to the cover sheet and stringers is equivalent to a chordwise cut equal to the projected length of the actual cut.

Types of damage.- Because of the random nature of the cut orientation relative to the wing chord and the foregoing assumptions, it was felt advisable to consider only the following general types of damage for this investigation:

(1) Various length continuous chordwise cuts through both the upper and lower cover sheets and stringers. Each cut is considered to be centered between the spars. (See fig. 3(a).)

(2) Various length continuous cuts through one rib and both upper and lower cover sheets. Each cut is assumed to be centered on the rib and at a slight angle to the plane of the rib. (See fig. 3(b).)

(3) A cut through either the front or rear spar. This damage is considered to sever completely the upper and lower spar caps and the web. (See fig. 3(c).)

(4) A cut through one spar and one rib. This cut is considered to be located near the rib-spar junction but does not include any stringers. (See fig. 3(d).)

Estimates of the reduction in structural strength.- The amount of work involved in making a complete structural analysis of the B-29 airplane to include the types of damage listed above and the possible combinations of this damage would be several times the work required for the original stress analysis of the B-29. Therefore, the following estimates in the reduction in structural strength of the primary wing structure of the B-29 are deduced from elementary calculations and engineering judgment.

The results of the investigation are given in figure 4 as the estimated reduction in structural strength for the four types of damage considered. A brief discussion of the analysis procedure and sample calculations for bay (a) (station 42 to 136) are presented in the appendix.

Although the results presented herein do not include analyses of the fuselage and tail surfaces, it is believed that, because of similar construction of the wing and tail surfaces, the results presented for the wing will generally apply to the tail as regards structural damage. For the fuselage, it is felt that approximately 50 percent of the structural material must be removed from a section of the fuselage, excluding the bomb-bay region, to cause structural failure.

DISCUSSION OF RESULTS

From the results shown in figure 4, the following general observations can be made:

(1) A 10-second structural kill of the airplane cannot be obtained by a full chordwise cut through the cover sheets and stringers. This result is obtained because the spar flanges will behave as short columns across the cut and are capable of carrying load well above the yield stress of the material. The lower spar flanges alone are capable of carrying the tension load. The spar webs are capable of carrying the vertical shear load plus the torsion load in vertical shear. The margin of strength remaining after a full chordwise cut, however, is small enough that other factors such as a deflection of the aileron may be enough to cause failure.

(2) A cut through one rib and the cover sheets and stringers can produce a 10-second structural kill of the airplane. Damage to a rib effectively increases the rib spacing so that, if enough cover sheet and stringers are cut, the upper spar flanges can buckle. There is also an appreciable reduction in torsional strength due to damage to a rib and adjacent cover sheet.

(3) The cutting of one spar can produce a 10-second structural kill only at a section with a large cutout. At a section with a cutout, the one remaining spar and one cover sheet and stringers will be structurally unstable under the combined lg loads. If the spar is cut at a section without a cutout, the cover sheets and stringers are capable of transferring the spar loads around the cut.

(4) A 10-second structural kill can be obtained by cutting one spar and one rib. The cutting of either rib adjacent to the spar cut prevents

the transfer of spar loads around the cut and, in addition, increases the effective rib spacing and allows the undamaged spar and cover sheets to become less stable.

The reductions in structural strength shown in figure 4 can be added to a certain extent to obtain a measure of the total damage although most of the effects of the cuts cannot be added in a 1:1 ratio. In general, the extent to which the damage is additive can be stated as follows:

(1) The cuts must be in a section between two ribs if the ribs are undamaged.

(2) Damage to the cover sheets and stringers is additive only to the extent that common stringers are not cut.

(3) Damage to a spar and to the cover sheets and stringers are additive between ribs, particularly if the cover damage is extensive or near the spar cut.

(4) In general, the effect of damage between two undamaged ribs is additive but reasonable care must be taken in determining the contribution of each cut to the over-all reduction in structural strength.

Throughout this investigation, no consideration has been given to the redistribution of the spanwise loadings due to a change in angle of attack caused by damage to the wing structure. Changes in the air load are produced by some types of damage, particularly damage to the spars.

CONCLUDING REMARKS

It has been found by an elementary type of aerodynamic analysis based on static-stability consideration that at least 42 percent or 29.7 feet of the tip of one wing panel including the entire aileron must be removed in order to produce irrevocable loss of control of the Boeing B-29 airplane. The remaining inboard part of the wing panel has been considered to be the region in which structural failure must occur to produce a kill of the aircraft within 10 seconds. This inboard part of the Boeing B-29 airplane wing was considered to be damaged by rod-type warhead fragments and the main wing structure was analyzed to obtain the estimated reduction in structural strength due to four general types of damage produced by the rod fragments. The extent to which structural strength is reduced by the assumed types of damage has been estimated by engineering judgment and elementary calculations.

The results of the structural analysis indicate that the Boeing B-29 airplane wing is relatively invulnerable to 10-second-kill damage to the structure by rod-type fragments. In general, unless a spar is cut the damage must effectively encompass all structural material between spars.

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APPENDIX

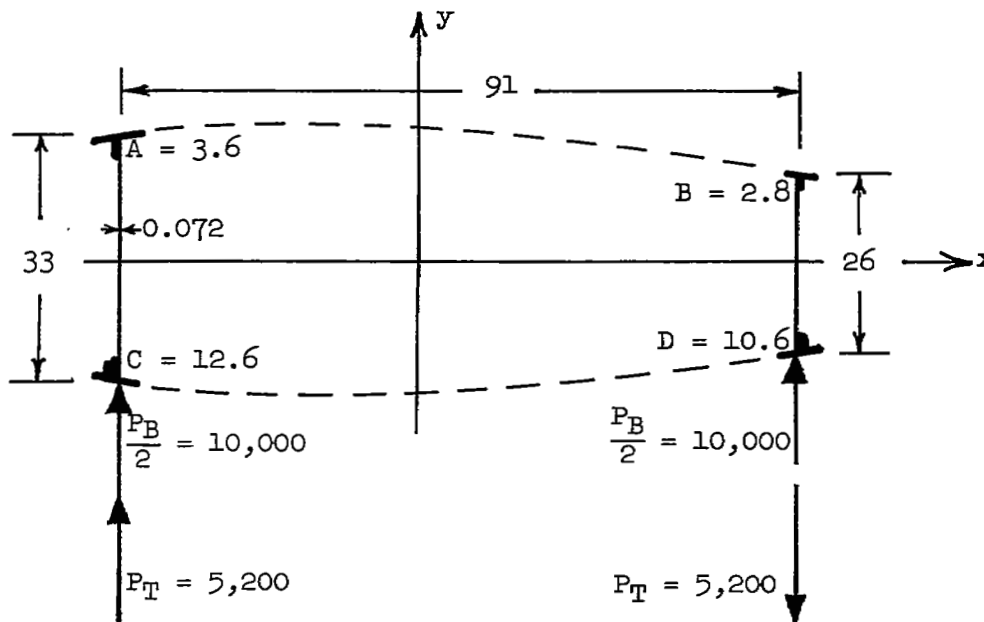
SAMPLE CALCULATIONS FOR BAY (a)

If all the cover sheets and stringers between spars are cut, the torque must be carried by the spar webs and flanges as vertical shear. The net beam shear and net torque at station 100 for lg loading are

$$T = 470,000 \text{ lb/in.}$$

$$P_B = 20,000 \text{ lb}$$

If the shear and torsion are assumed to be distributed to the spars as shown in the following sketch



If the shear is carried by the spar webs only

$$\tau t = \frac{15,200}{33} = 460 \text{ lb/in. (front spar)}$$

Shear stress on front spar web

$$\tau = \frac{460}{0.072} = 6,400 \text{ lb/sq in.}$$

and the allowable shear stress (ref. 5) is 24,800 pounds per square inch. Therefore, the shear web is not critical.

When the same configuration as shown in the preceding sketch is used, the stresses in the spar flanges due to the combined action of beam and chord bending moments are determined as follows:

$$M_B = 9.76 \times 10^6 \text{ lb-in.}$$

$$M_C = -620,000 \text{ lb-in.}$$

$$I_x = 4570 \text{ in.}^4$$

$$I_y = 63,850 \text{ in.}^4$$

$$\sigma = \frac{M_B y}{I_x} + \frac{M_C x}{I_y}$$

For flange A (compression)

$$\sigma = 55,400 \text{ lb/sq in.}$$

For flange B (compression)

$$\sigma = 43,500 \text{ lb/sq in.}$$

For flange C (tension)

$$\sigma = 14,800 \text{ lb/sq in.}$$

For flange D (tension)

$$\sigma = 13,000 \text{ lb/sq in.}$$

If the yield stress of the flange material is assumed to be the upper limit of the structural strength, the two upper flanges are above the critical stress. Although the stresses in the upper flanges are above the yield stress of the material, the flanges act as short columns across a narrow slit and hence can carry the load without buckling.

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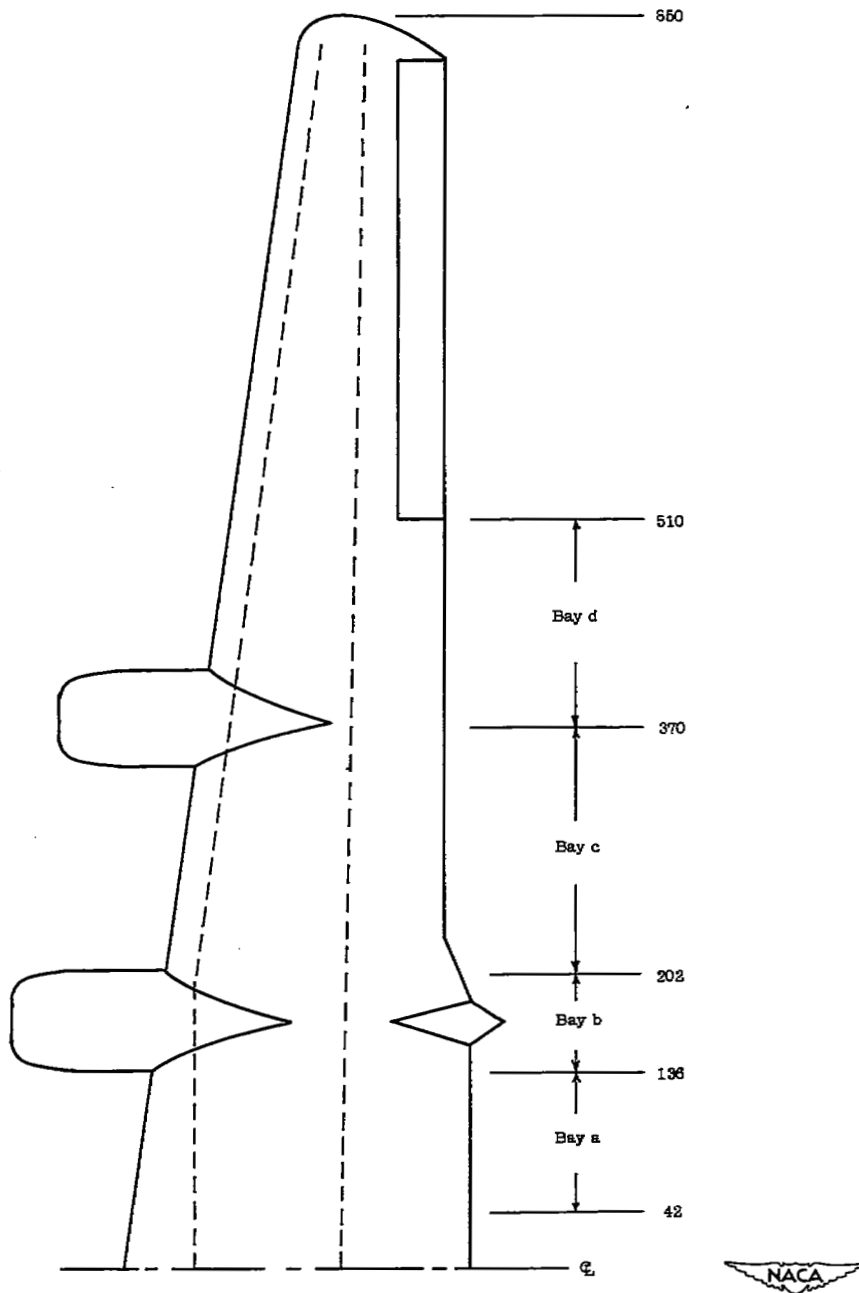


Figure 1.- Boeing B-29 wing panel showing the four structural bays considered.

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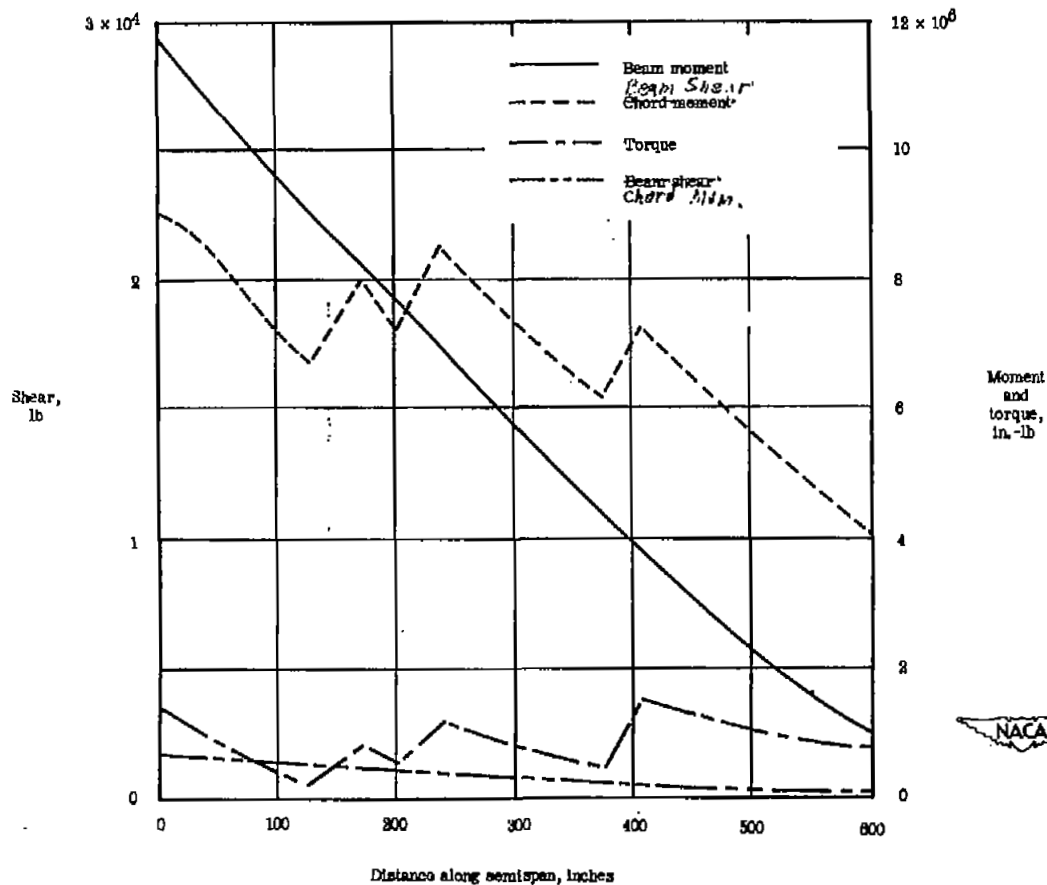
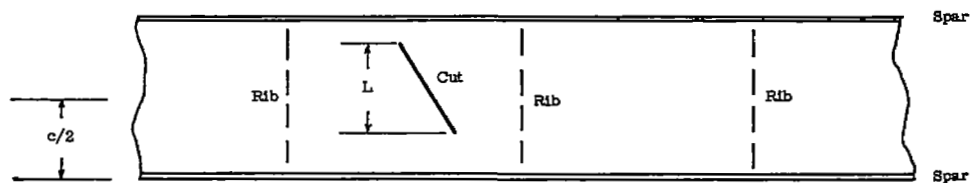
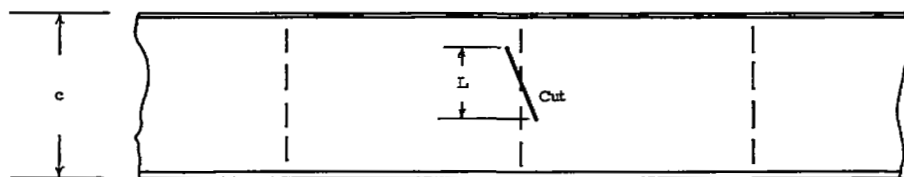


Figure 2.- Shear, moments, and torsion for the Boeing B-29 airplane with full bomb load and reduced fuel load for a net wing loading of 1 g.

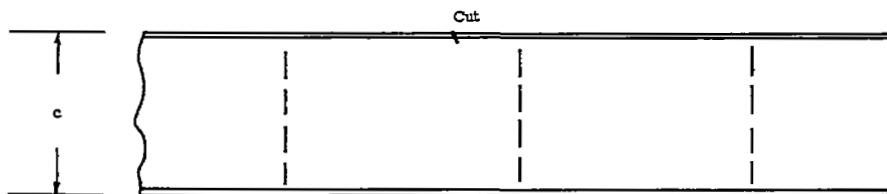




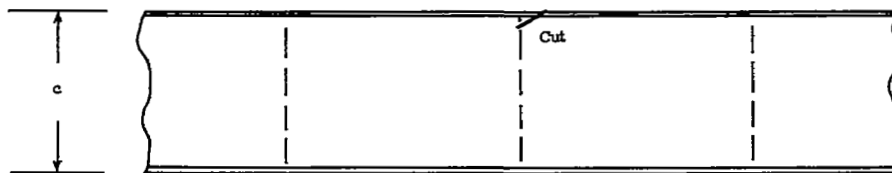
(a) Chordwise cut through cover sheets.



(b) Cut through one rib and cover sheets.

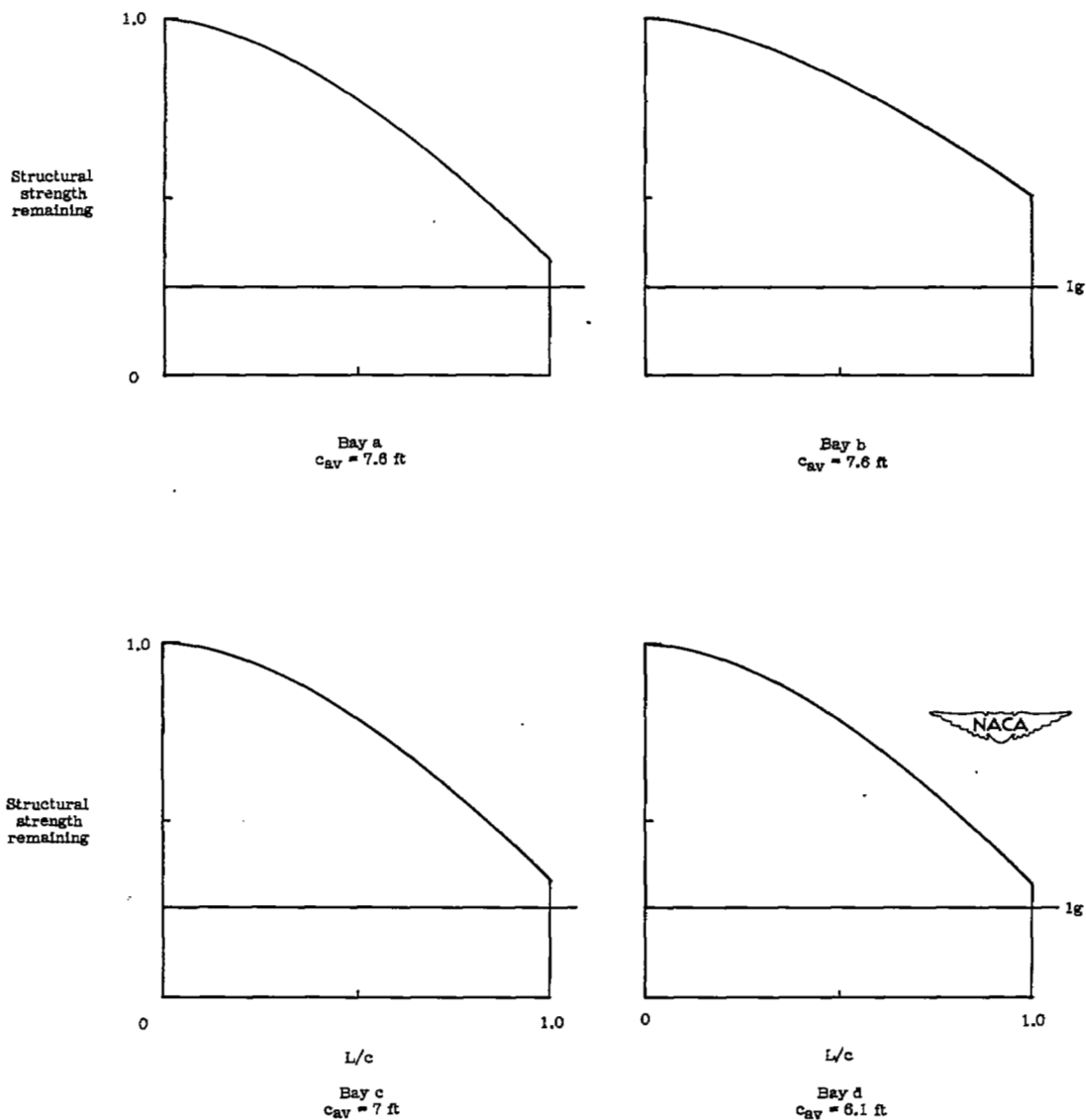


(c) Cut through one complete spar.



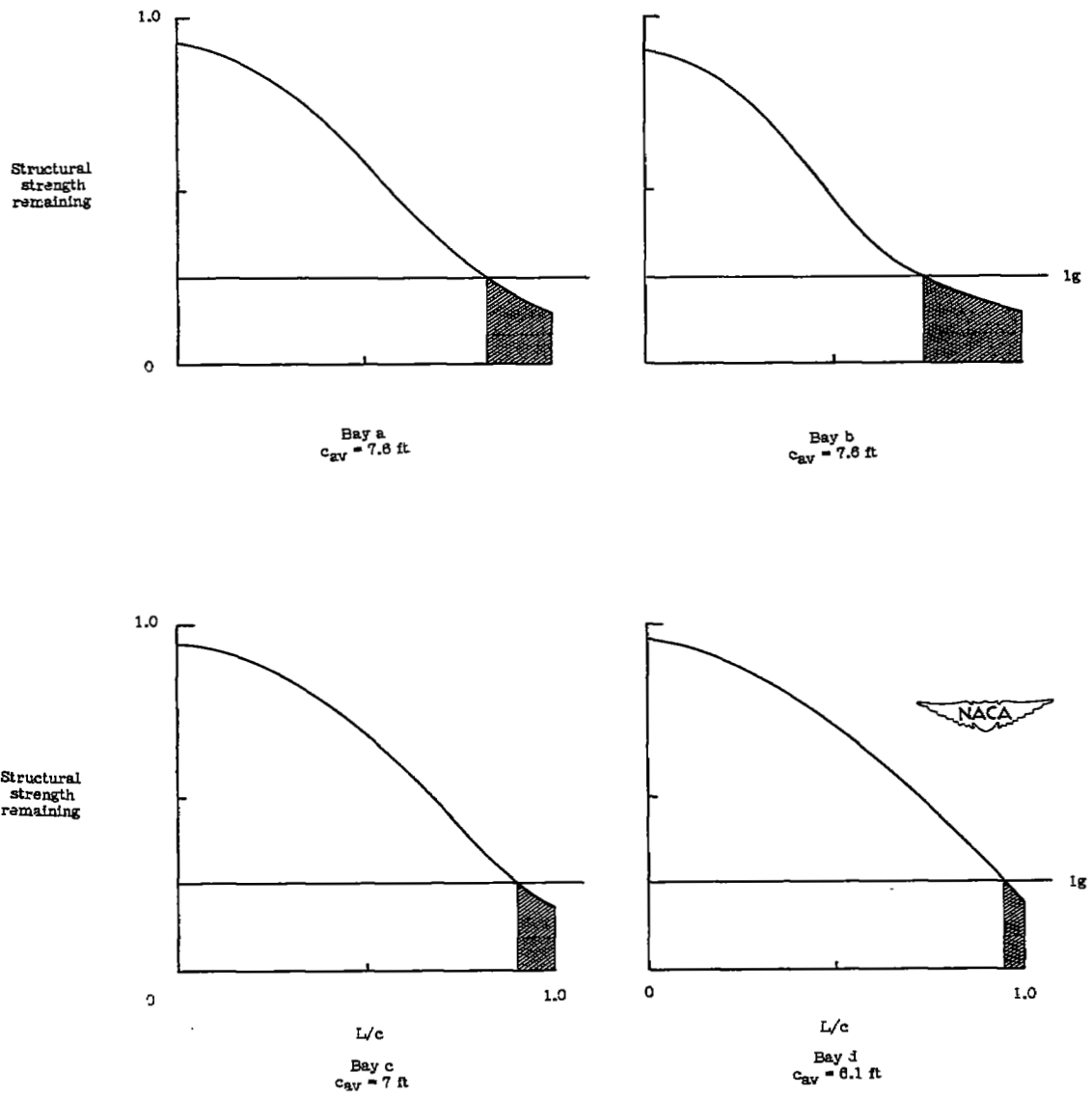
(d) Cut through one spar and one rib.

Figure 3.- General types of damage considered in investigation.



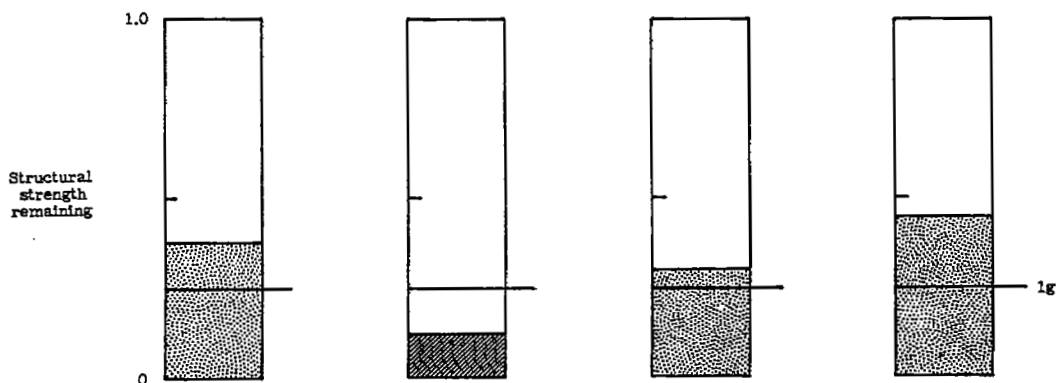
(a) Chordwise cut through cover sheets.

Figure 4.- Estimated reduction in structural strength due to cuts from rod-type fragments.

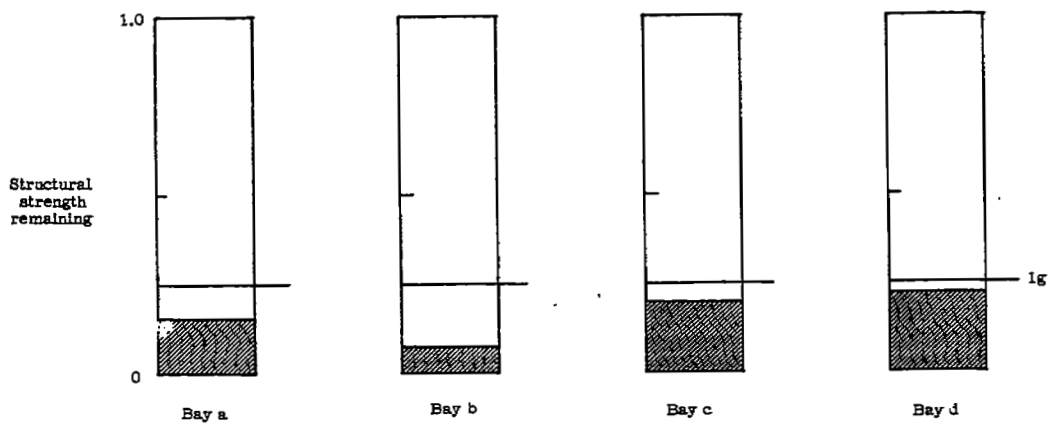


(b) Cut through one rib and cover sheets.

Figure 4.- Continued.



(c) Cut through one complete spar.



(d) Cut through one spar and one rib.

Figure 4.- Concluded.

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ABSTRACT

An elementary type of analysis has been used to determine the amount of wing tip that must be severed to produce irrevocable loss of control of a B-29 airplane. The remaining inboard structure of the B-29 wing has then been analyzed and curves are presented for the estimated reduction in structural strength due to four general types of damage produced by rod-type warhead fragments. The curves indicate the extent of structural damage required to produce a kill of the aircraft within 10 seconds.

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