R. & M. No. 3248

MINISTRY OF AVIATION

AERONAUTICAL RESEARCH COUNCIL
REPORTS AND MEMORANDA

Behaviour of Skin Fatigue Cracks at the Corners of Windows in a *Comet* I Fuselage

By R. J. Atkinson, W. J. Winkworth and G. M. Norris

LONDON: HER MAJESTY'S STATIONERY OFFICE
1962
FOURTEEN SHILLINGS NET

Behaviour of Skin Fatigue Cracks at the Corners of Windows in a *Comet* I Fuselage

By R. J. Atkinson, W. J. Winkworth and G. M. Norris

Communicated by the Deputy Controller Aircraft (Research and Development), Ministry of Aviation

*Reports and Memoranda No. 3248**
June, 1960

Summary. Fatigue tests on a *Comet* I pressure cabin subjected to operational pressure cycles are described. Cracks at window corners are the main subject of investigation. Results are compared with earlier experiments on other *Comet* I pressure cabins. Conclusions are reached that appear to have some general significance.

1. *Introduction.* Fatigue investigations made on one of a number of *Comet* I fuselages that had been specially provided for research purposes are described in this Report. In these investigations the pressure cabin was subjected to pressure loading cycles only, and attention was directed mainly to the initiation and development of cracks at the window corners. Special care was taken to avoid unnecessary destruction, and cracks were repaired as necessary to prevent catastrophic failure. Nine cracks out of a total of sixteen actually reached the stage where sudden extension appeared imminent.

Results are examined below in the light of earlier fatigue work on a *Comet* pressure cabin[1,2] subjected to wing loads as well as pressure. In the case of strain measurements, use is also made of the results from a static test to destruction[3] made on a third fuselage under pressure alone.

2. *The Test Specimen.* The fatigue tests were made on the fuselage of *Comet* I G-ALYR, (Fig. 1). This aircraft was built in 1952 and had made 747 pressurized flights. (*N.B.* All numbers of pressure cycles are totals, *i.e.*, service plus test cycles.) The diameter of the fuselage was 10 ft 3 in. and the pressure cabin was 70 ft long.

2.1. *Basic Structure.* The basic structure consisted of circumferential frames 21 inches apart, stringers at approximately 5·5 in. pitch, and the skin covering. The frames were of zed section, 2·75 in. deep and notched to take the witch-hat stringers which were bonded to the skin (Fig. 2). The skin was generally 22 s.w.g. (0·028 in.) except along the sides of the fuselage, where 20 s.w.g. (0·036 in.) skin contained the windows (Fig. 3). Skin material was D.T.D.546 (Appendix).

Attachment between the skin-stringer panels and the frames was usually by 2 B.A. countersunk-head bolts at the stringer flanges only. In the centre section, however, the skin was additionally riveted to the frames (Fig. 4), in the region of the windows.

* Previously issued as R.A.E. Report No. Structures 257—A.R.C. 22,270.

2.2. *Local Structure at Windows and Escape Hatches.* With the exceptions of the two forward escape hatches, which interrupted a circumferential frame (Fig. 6), the windows and escape hatches were positioned between the frames.

The windows and escape hatches were rectangular, their relative sizes being:

Window: $16 \cdot 6$ in. wide $\times$ 14 in. high, corner radii 3 in.

Escape hatch: $19 \cdot 0$ in. $\times$ $21 \cdot 5$ in. high, corner radii 4 in. (*see* Fig. 5).

The apertures were reinforced by peripheral members of zed section bonded to the skin with Redux adhesive and additionally riveted by $\frac{1}{8}$ in. countersunk-head rivets at the corners (Figs. 7 to 11).

3. *Method of Test.* Supported on its wing centre section in a tank, the fuselage was filled with water and completely submerged in water, internal pressure being applied by pumping in more water. The cycling action was controlled by pressure switches.

No loads other than those due to internal pressure were applied. The cycles were repeated pressure cycles of the form given in Fig. 12; the peak pressure was $8 \cdot 25$ p.s.i. and the loading cycle took about 65 seconds.

Detailed visual inspections were made at frequent intervals. When a fatigue crack was found its subsequent development was observed continuously with an inverted periscope. When it was judged that a fatigue crack would soon develop catastrophically the affected aperture was repaired to prevent excessive damage to the specimen (Fig. 13).

By means of resistance-wire strain gauges, strains were measured at selected window and escape-hatch corners before the fatigue test was started.

4. *Results.* 4.1. *Measured Strains.* Readings from strain gauges positioned at the corners of the third starboard window and the forward port escape hatch were taken at increments of pressure. Stresses were deduced for a pressure of $8 \cdot 25$ p.s.i. (Figs. 14 to 19). The highest stresses are as given in Table 1.

4.2. *Fatigue Test.* A total of 11,319 pressure cycles of 0 to $8 \cdot 25$ p.s.i. to 0 were applied to the fuselage. Fatigue cracks occurred in the skin at the corners of nine windows and two escape hatches, sixteen corners being affected (Table 2 and Fig. 20). No fatigue cracks occurred at the A.D.F. aerial hatches (at which the 22 s.w.g. reinforcing plates were subsequently removed for examination of the skin underneath), the crew and passenger doors, or at the freight hatches.

The first crack was seen at 5,248 cycles at the third window on the port side, *i.e.*, the window just forward of the rear spar frame, and by 8,941 cycles all six windows in the centre section had fatigue cracks at one or more of their corners.

Nine fatigue cracks were observed continuously throughout their growth; six at windows in the centre section, one at a window in the aft section, and two at the port forward escape hatch. The fatigue cracks originated at the rivet holes at the aperture corners, not at the aperture edges, and when first seen were usually about $0 \cdot 25$ in. long. Development away from the aperture was initially about 1 in. in 500 pressure cycles, and, as all the windows were located between frames, the growing crack invariably had to cross a frame when approximately $4 \cdot 5$ in. long. When the cracks had spread 2 in. or so past the frames, *i.e.*, were about $6 \cdot 5$ in. long, they were judged to be critical in that the application of a few more cycles would cause a catastrophic failure.

Differences of behaviour occurred during growth towards the frames and across the frames. During the first stage, several cracks became critical when about 3 in. long, *i.e.*, between the aperture and the frame. This condition was noted at most of the windows in the centre section where the skin was also riveted to the frames. The presence of this extra attachment appeared to have a strong influence in delaying crack growth across the frame, and was clearly demonstrated in the case where a crack extended a distance of 2 in. in one pressure cycle (Fig. 22). An exception however, occurred at the port forward escape hatch (where the riveted frame was a partial frame only—Fig. 6) when the crack at the bottom forward corner caused a catastrophic failure when 2·75 in. long (Fig. 6).

The growth of one crack was observed in detail at a window in the aft portion of the fuselage where the skin was not riveted to the adjacent frame. No critical stage occurred at 3 in., the crack grew uninterruptedly across the frame to a critical length of 7·1 in. This behaviour was also shown in a crack at a window in the same section of G-ALYU[4] (Fig. 30).

In crossing the frames the cracks behaved in various ways:

(1) The frame with the normal bolted attachment appeared to have no influence whatever on crack growth.

(2) Where the skin was riveted to the frames:

(*a*) Cracks passing between rivet holes were slowed down, but not stopped altogether.

(*b*) Cracks entering rivet holes were stopped temporarily; *e.g.*, one crack was contained for more than 1,800 cycles.

Development beyond the frames progressed for about 2 in. when it was evident that catastrophic failure was imminent. Generally it was possible to stop the test before the fast-running stage, but four catastrophic failures did occur either because of misjudgment of rates of growth or of the difficulty involved in observing more than two cracks at the same time.

Table 4 summarises the data on critical crack lengths. Curves of crack growth are plotted in Figs. 21 to 29; photographs of typical cracks are given in Figs. 31 to 36 (Table 3).

5. *Discussion.* 5.1. *Origins of the Fatigue Cracks.* All the fatigue cracks originated at the countersunk rivet holes in the skin at the window and escape hatch corners. Those cracks which eventually became catastrophic started at outer-row rivet holes. The few cracks that originated at holes in the inner row grew inwards to the edge of the aperture and did not become catastrophic. No cracks originated at the edges of the apertures.

As indicated by the strain measurements, the stress at the corner of an aperture attained its peak value at the edge; at the outer row of rivet holes it was about 20,000 p.s.i. or perhaps half the stress at the edge. The presence of a sharp-edged (countersunk) rivet hole in a high stress field might, however, increase the stress locally, perhaps by a factor of 3, and, in addition, there would be a certain amount of fretting action, so it is reasonable to expect fatigue cracks to be initiated at the rivet holes.

5.2. *Locations of the Fatigue Cracks.* The test on G-ALYR showed that fatigue cracks were initiated earliest and most numerously at the windows in the centre section, and though the first failure in G-ALYU was at a forward escape hatch[4], fatigue cracks had also formed at several windows in the centre section by the time of this failure (Fig. 37).

That the fatigue cracks should occur first at the corners of the apertures is easily explainable in that the general level of stress there is some two to three times that found elsewhere in the fuselage.

The tendency for cracks to occur first in the centre section may be explained by a combination of three reasons. First, the average stress in the skin at the corners of the windows would appear to be some 20 per cent greater than at the corners of the escape hatches, as is shown by the strain measurements made on three different fuselages (Table 5); in this connection it should be noted that the radius at the corner of a window is smaller, 3 in. compared with 4 in. for the escape hatch. Second, it is possible that there were aggravating distortions in the centre section of the cabin due to the reaction of the internal pressure by the floor instead of by a complete cylinder as elsewhere. Third, the effect of previous service use should not be forgotten, in that the shear stresses from the usual flight and ground loads are highest in this part of the fuselage.

5.3. *Propagation of the Fatigue Cracks.* Many of the cracks when first observed were about 0·25 in. long. This is relatively short, but it is pointed out that the conditions for observing cracks during the test were exceptional as they were anticipated at the corners of the apertures and the paint was removed for easy inspection. It is problematical whether under normal service conditions the cracks would have been detected so early.

Even if it were certain that cracks of this length could be found easily, the curves show that a crack length of 0·25 in. corresponds to about 90 per cent of the total life when no remedial action is taken. Coupled with this fact is the indication that the rate of propagation is probably greater in service than on test, since the crack measured at a window in G-ALYU, with its more representative loading[2], developed 2 to 6 times as fast as the cracks in G-ALYR.

The delaying effect of the adjacent riveted frame provided a temporary barrier when the cracks were about 4 in. long. Nevertheless the opinion was formed that special inspection procedures would have to be used to ensure reliable detection. In this connection inspection would be greatly eased if the fuselage were partly pressurized to open up the cracks.

Comparison of these findings with observations from tests on flat sheets and simple cylinders shows at once that the flat-sheet tests were unrealistic because of the absence of radial pressure.

There appears to be some measure of agreement between the window-corner cracks and those induced in 12 ft diameter cylinders in that critical lengths and numbers of cycles to failure were of the same order for a roughly comparable nominal stress cycle, but upon consideration of the differing conditions between the window corners and in the simple unstiffened cylinders, such agreement is perhaps fortuitous.

5.4. *Interpretation of the Fatigue-Test Results.* The meagre data make reliable analysis impossible, but certain features need comment. First, the initial failure in G-ALYR occurred at approximately twice the number of cycles as that in G-ALYU. Second, a closer grouping is evident of the failures in G-ALYU compared with G-ALYR (Fig. 37). Third, rate of crack growth in G-ALYU was about four times that in G-ALYR.

From this evidence it appears that fatigue performance is adversely affected to an appreciable extent by other-than-pressure loads reaching the cabin, an effect already noted by Walker[1,2]. This means that where accurate life estimates are required to be obtained from tests the general flying and landing loads should be reproduced as faithfully as practical considerations allow. Furthermore, since perfection in this respect is unlikely, an allowance must be made for inadequacies of representation.

6. *Concluding Remarks.* This Report contains material from which various conclusions may well be drawn, and especially if combined with later work. Three points, however, appear to be established.

(i) The simplifications in fatigue loading which are generally accepted to make a full-scale test practicable are likely to give a longer life than would be realised in service.

(ii) The attachment of reinforcing material inevitably introduces its own stress concentrations; the example of the countersunk rivet holes at the window corners illustrates this important principle.

(iii) Nearly all the fatigue life associated with a particular crack may have been expended by the time the crack first becomes noticeable.

REFERENCES

No.	Author		Title, etc.
1	P. B. Walker	..	Pressure cabin fatigue. 5th International Conference, Los Angeles, 1955.
2	P. B. Walker	..	Pressure cabin fatigue. *Aircraft Engineering*. Vol. XXVIII. January, 1956.
3	P. B. Walker	..	Static strength tests of a *Comet* I pressure cabin. A.R.C. 18,359. December, 1955.
4	H.M.S.O...	..	Civil Aircraft Accident. Report of the Court of Inquiry—C.A.P. 127. December, 1955.

APPENDIX

The Materials Used in the Structure

1. D.T.D.687A.—Clad, high-tensile aluminium-alloy sheet.

(i) *Chemical composition* (nominal)

Copper	0·4 per cent
Zinc	5·3 per cent
Magnesium	2·7 per cent
Manganese	0·5 per cent
Aluminium	The remainder.

(ii) *Heat treatment*

Quenched after 2 to 10 hours at 455 to 465 deg C.

Aged 4 to 30 hours at 120 to 140 deg C, or appropriate to suit requirements.

(iii) *Strength properties*

(*a*) 0·1 per cent proof stress: not less than 27 tons/sq in.

(*b*) Ultimate tensile stress: not less than 32 tons/sq in.

2. D.T.D.610

(i) *Chemical composition*

Copper	Not less than 3·5, nor more than 4·8 per cent
Iron	Not more than 1·0 per cent
Silicon	Not more than 1·5 per cent
Magnesium	Not more than 1·0 per cent
Manganese	Not more than 1·2 per cent
Titanium	Not more than 0·3 per cent
Aluminium	The remainder.

(ii) *Heat treatment*

Quenched from 500 to 510 deg C at 2 to 4 hours.

Aged 5 days at room temperature (W condition).

(iii) *Strength properties*

(*a*) 0·1 per cent proof stress: not less than 14 tons/sq in.

(*b*) Ultimate tensile stress: not less than 24 tons/sq in.

(*c*) Elongation: not less than 12 per cent on sheets up to $\frac{3}{8}$ in. thick.

3. D.T.D.546B.—Clad, high-tensile aluminium-alloy sheet.

(i) *Chemical composition.* Same as for D.T.D.610.

(ii) *Heat treatment*

Quenched from 500 to 510 deg C at 2 to 4 hours.

Aged at 155 to 205 deg C for an appropriate time. (WP condition.)

(iii) *Strength properties*

(*a*) 0·1 per cent proof stress: not less than 20 tons/sq in.

(*b*) Ultimate tensile stress: not less than 26 tons/sq in.

(*c*) Elongation: not less than 8 per cent for sheets thicker than 12 s.w.g.

TABLE 1

Highest Stresses Measured at the Edges of the Apertures
for an Internal Pressure of 8·25 *p.s.i.—G-ALYR*

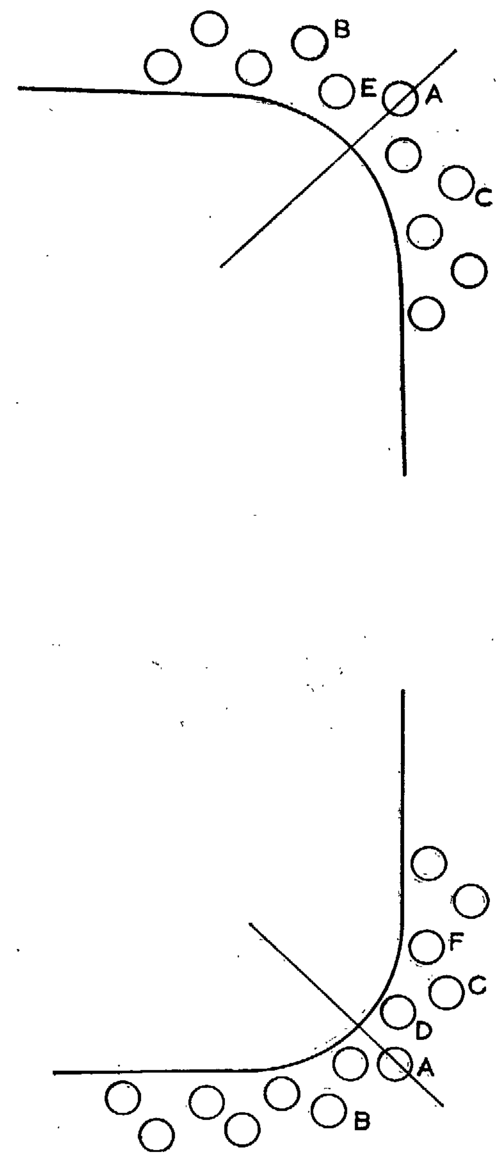
Aperture corner	Third starboard window		Forward port escape hatch	
	Top rear	Bottom rear	Top rear	Bottom rear
Stress obtained by extrapolating to aperture edge, p.s.i.	47,700	35,500	40,000	32,700
Highest 'strain-gauge' stress, p.s.i. (*see* Figs. 14–17)	40,800	32,800	33,250	27,500
	Rear aerial hatch			
	Port forward	Starboard rear		
Stress obtained by extrapolating to aperture edge, p.s.i.	33,000	34,400		
Highest 'strain-gauge' stress, p.s.i. (*see* Figs. 18–19)	32,850	30,450		

TABLE 2

Chronological Occurrence of the Fatigue Cracks at the Aperture Corners

Aperture			Side of fuselage	Corner of aperture	Origin of fatigue crack rivet hole	Crack length when first seen (inches)	Pressure cycles
Windows between spar frames (Centre section)	Other windows	Escape hatch					
3rd			Port	Bottom forward	A	0·20	5,248
1st			Port	Bottom rear	B	0·50	6,542
1st			Starboard	Top forward	C	3·40†	6,901
3rd			Starboard	Bottom forward	D	0·17*	6,901
2nd			Port	Bottom rear	C	0·06	6,901
	6th		Starboard	Top rear	E	0·14* (Rivet hole oversize)	6,901
2nd			Port	Top forward	C	0·10	6,959
3rd			Starboard	Top rear	C	1·62	7,692
2nd			Port	Top rear	A	0·04	8,564
		Forward	Port	Bottom forward	B	0·08	8,564
	4th		Port	Top rear	A	0·51	8,941
	4th		Port	Bottom forward	F	0·70	9,225
	6th		Port	Bottom forward	A	0·06	9,350
2nd			Starboard	Top forward	A	0·75	10,016
		Forward	Port	Bottom rear	A	0·31	10,016
		Forward	Starboard	Top rear	C	0·10	11,286

* Between rivet hole and edge of aperture.
† Crack had spread to frame before it was discovered.



Rivet holes at which the cracks occurred.

TABLE 3

Growths of the Fatigue Cracks

Location of the fatigue cracks					When first seen		When the crack had reached the adjacent frame					Final details				Remarks and action taken
Window		Escape hatch	Corner	Side	Crack length (in.)	Pressure cycles	Crack length (in.)	Additional cycles from when first seen	Did crack spread into a frame rivet hole?	Growth in inches per cycle	Delaying effect of frame in cycles	Length (in.)	Additional cycles from when first seen	Growth in inches per cycle	Total pressure cycles	
Between spars	Outside spars															
3rd			Bottom forward	Port	0·20	5,248	4·40	700	No	0·009	90	6·25†	794	0·10	6,042	Catastrophic failure imminent. Aperture repaired.
1st			Bottom rear	Port	0·50	6,542	4·70	359	No	0·021	60	6·75†	417	0·06	6,959	Catastrophic failure imminent. Aperture repaired.
1st			Top forward	Starboard	3·40*	6,901	3·40	0, had reached adjacent frame when first seen	Yes	Stopped at rivet hole	>1,820	6·41†	2,040	0·05	8,941	Catastrophic failure imminent. Aperture repaired.
	6th		Top rear	Starboard	0·14	6,901	—	—	No, frame not riveted	—	—	About 12 feet	2,040	—	8,941	Catastrophic failure requiring major repair involving three starboard apertures.
3rd			Top rear	Starboard	1·62	7,692	3·15	168	Yes	Stopped at rivet hole	240	5·85†	873	0·03	8,564	Catastrophic failure imminent. Aperture repaired.
2nd			Top forward	Port	0·10	6,959	3·35	1,501	Yes	Stopped at rivet hole	890	15·0	2,449	Instantaneous failure	9,350	Catastrophic failure, only stopped by the patch around neighbouring window. Major repair.
		Forward	Bottom forward	Port	0·08	8,564	Crack spread catastrophically before reaching the circumferential frame—was about 2·75 in. long when failure occurred.					About 15 feet	2,682	Instantaneous failure	11,246	Catastrophic failure from front spar frame (18) to between frames 8 and 9. Major repair.
	4th		Top rear	Port	0·16	8,941	3·40	669	No, frame not riveted	No discontinuous kink observable in crack growth curve		7·10	725	Instantaneous failure	9,666	Catastrophic failure in 9,666th cycle running from 7·10 in. to about 12 feet. Major repair.
2nd			Top forward	Starboard	0·75	10,016	Crack grew to a length of 3·50 in., but was not allowed to reach the adjacent frame, as the aperture was reinforced.					3·50	229	—	10,245	Likely that crack would have grown further.
		Forward	Bottom rear	Port	0·31	10,016	3·35	1,189	No	0·1 approx.	When this crack had reached the circumferential frame at 11,205 cycles, a reinforcing strap was riveted close to the frame to prevent further crack progress, but at 11,246 cycles the crack at the forward corner caused a catastrophic failure.					

* *See* Figure 25. † Approximate critical length.

TABLE 4

Critical Crack Lengths

Aperture	Location	Critical crack length between the aperture and the adjacent frame (in.)	Critical crack length attained during final development (in.)
Port escape hatch (Bottom forward corner)	Forward section	2·75—at this length the crack caused a catastrophic failure	
Port escape hatch (Bottom rear corner)	Forward section	2·80	No result here because of the occurrence of the above failure
First window, port side	Centre section	2·45	6·75
First window, starboard side	Centre section	Crack had spread to the adjacent frame before any measurements were taken	6·41
Second window, port side	Centre section	No observable critical stage	No final length as this crack spread catastrophically from the frame
Second window, starboard side	Centre section	No observable critical stage	This aperture was repaired before crack had spread to the adjacent frame
Third window, port side	Centre section	3·10	6·25
Third window, starboard side	Centre section	No intermediate critical stage occurred	5·85
Fourth window, port side	Aft section	No intermediate critical stage occurred	7·10
Sixth window, port side * (G–ALYU)	Aft section	No intermediate critical stage occurred	5·60

* A previous fatigue test in which wing loads were applied as well as pressure loads.

TABLE 5

Measured Stresses at the Edges of Apertures in Three Fuselages, for an Internal Pressure of 8·25 *p.s.i.*

Fuselage	Aerial hatch*		Port forward escape hatch		Starboard forward escape hatch		Third window	
	Strain gauge	Extra-polated	Strain gauge	Extra-polated	Strain gauge	Extra-polated	Strain gauge	Extra-polated
G-ALYU	28,000	32,200	23,000†	26,500†	34,500	No reading	35,100	38,000
G-ALYR	32,850	34,400	33,250	39,600	No reading	No reading	40,800	47,700
G-ANAV	30,400	34,000	34,000	38,800	31,600	36,300	38,300	43,500

* The strain gauges attached at this aperture were cemented to the 22 s.w.g. reinforcing plate riveted over the skin.

† These stresses were measured after the escape hatch had been repaired following a catastrophic failure and may differ, therefore, from those that would have been measured in the original structure.

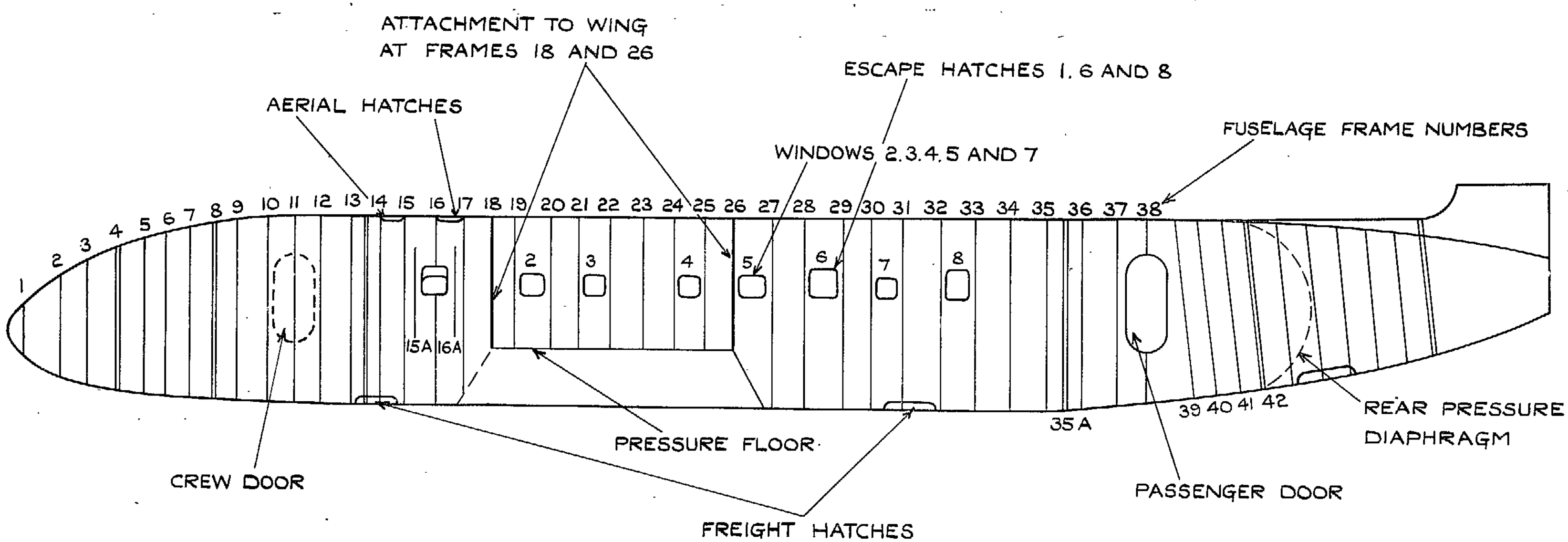


FIG. 1. The fuselage of *Comet* G–ALYR.

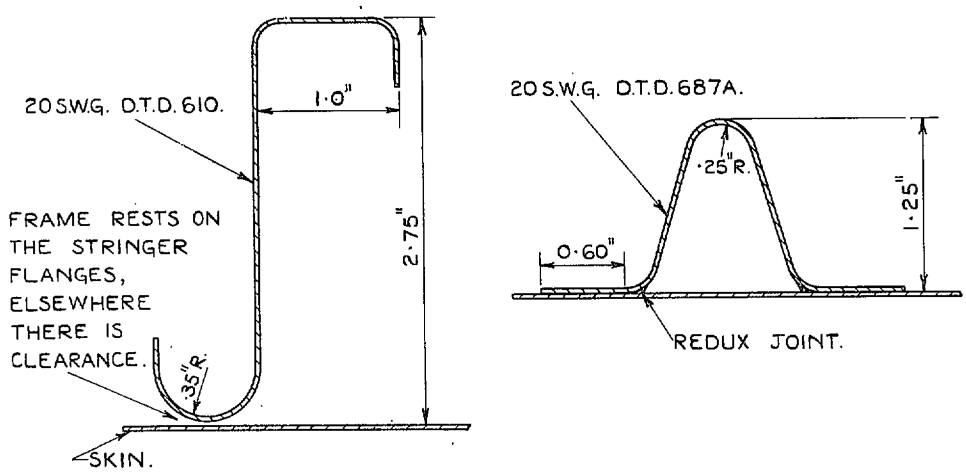


FIG. 2. Typical frame and stringer sections.

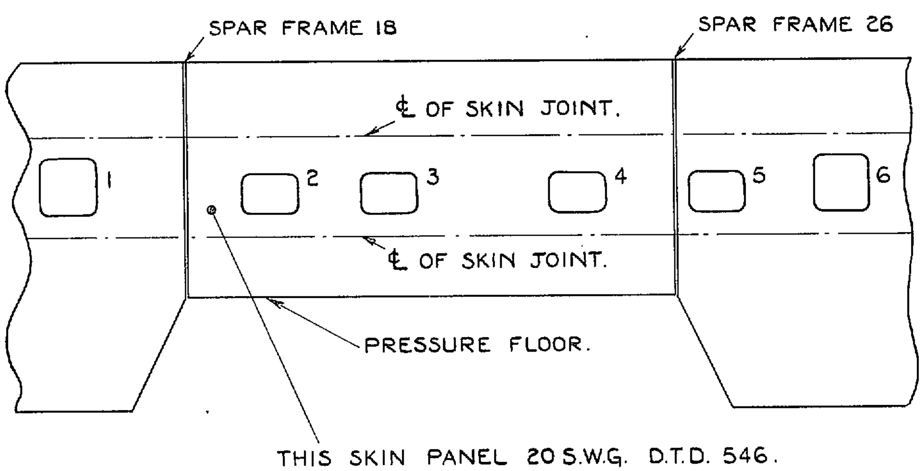


FIG. 3. Skin panel containing windows and escape hatches.

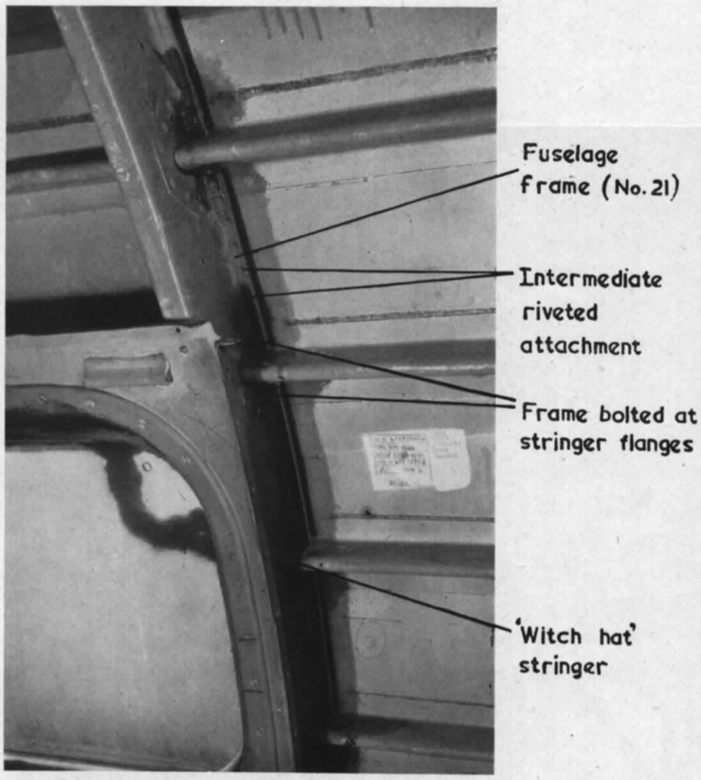


FIG. 4. Attachment of the skin to the frames.

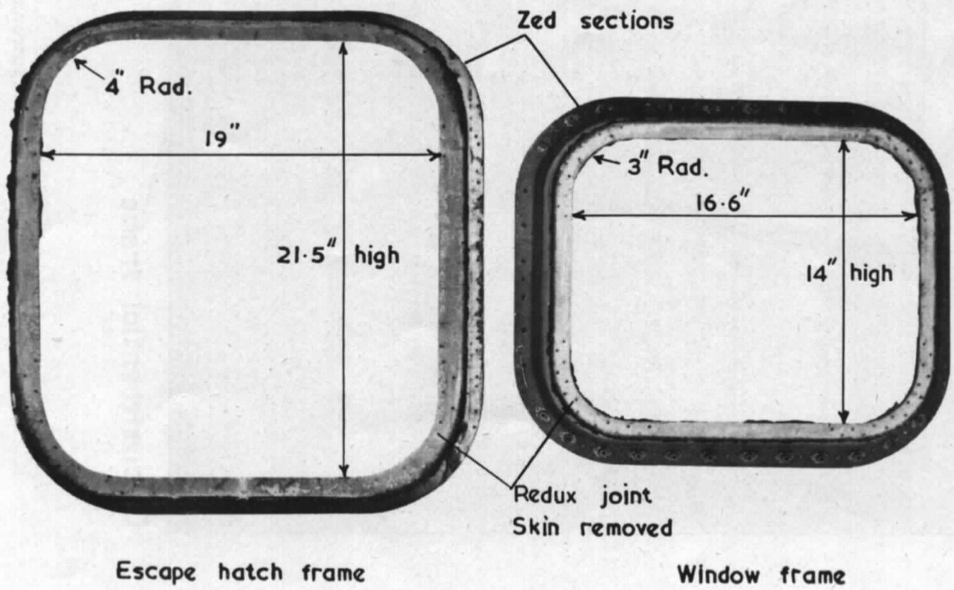


FIG. 5. Relative sizes of window and escape-hatch apertures.

(83824)

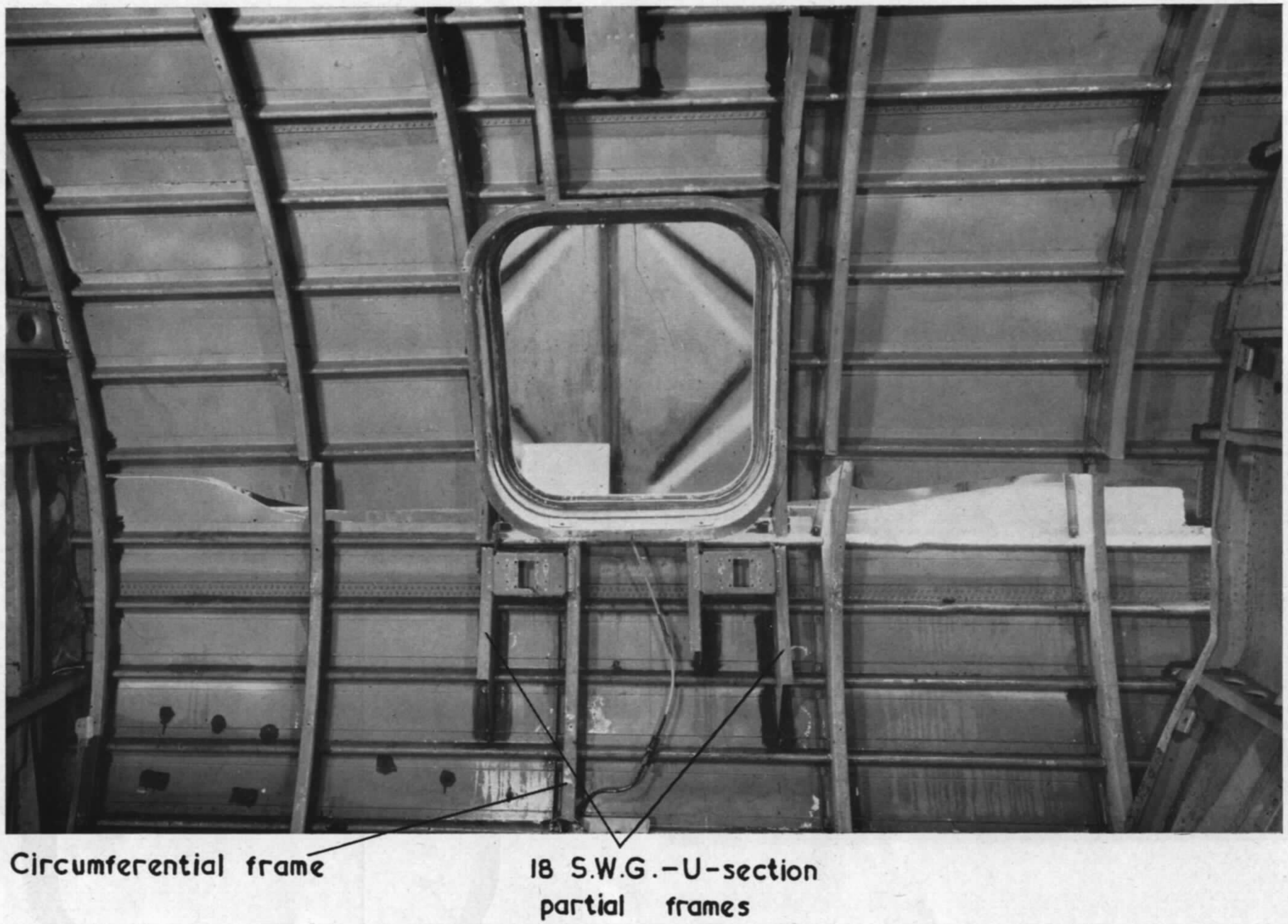
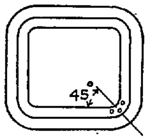


FIG. 6. Internal partial frames at forward escape hatches.
Failure at port forward escape hatch at 11,246 cycles.



LOCATION OF SECTIONS

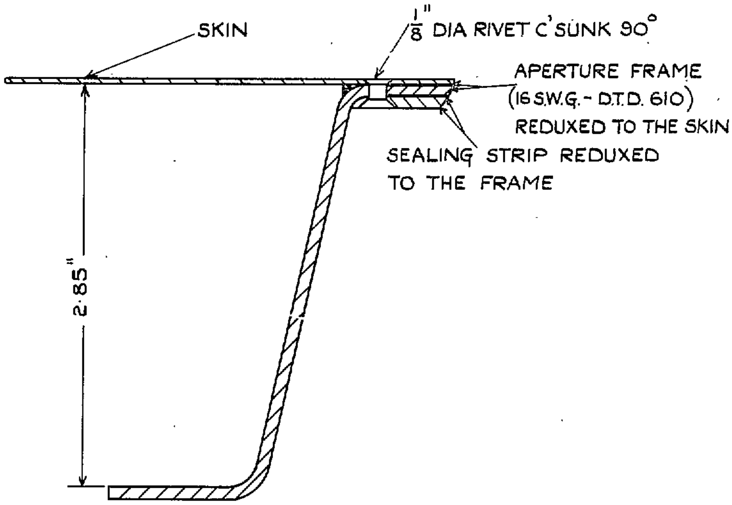


FIG. 7. SECTION THROUGH A WINDOW FRAME.

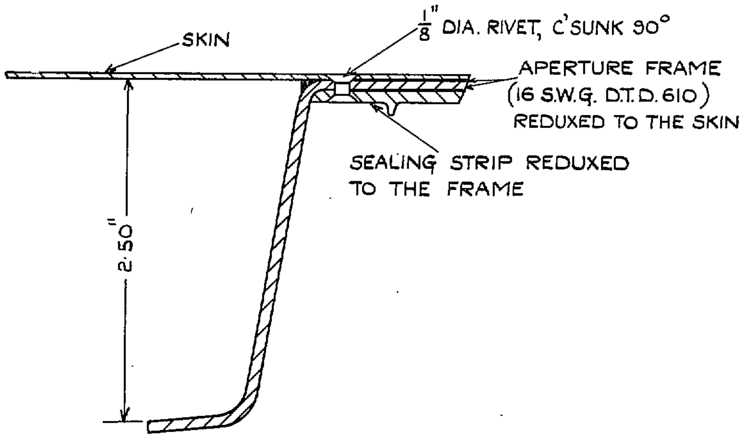


FIG. 8. SECTION THROUGH AN ESCAPE HATCH FRAME.

FIGS. 7 and 8. Sections through window and escape-hatch frames.

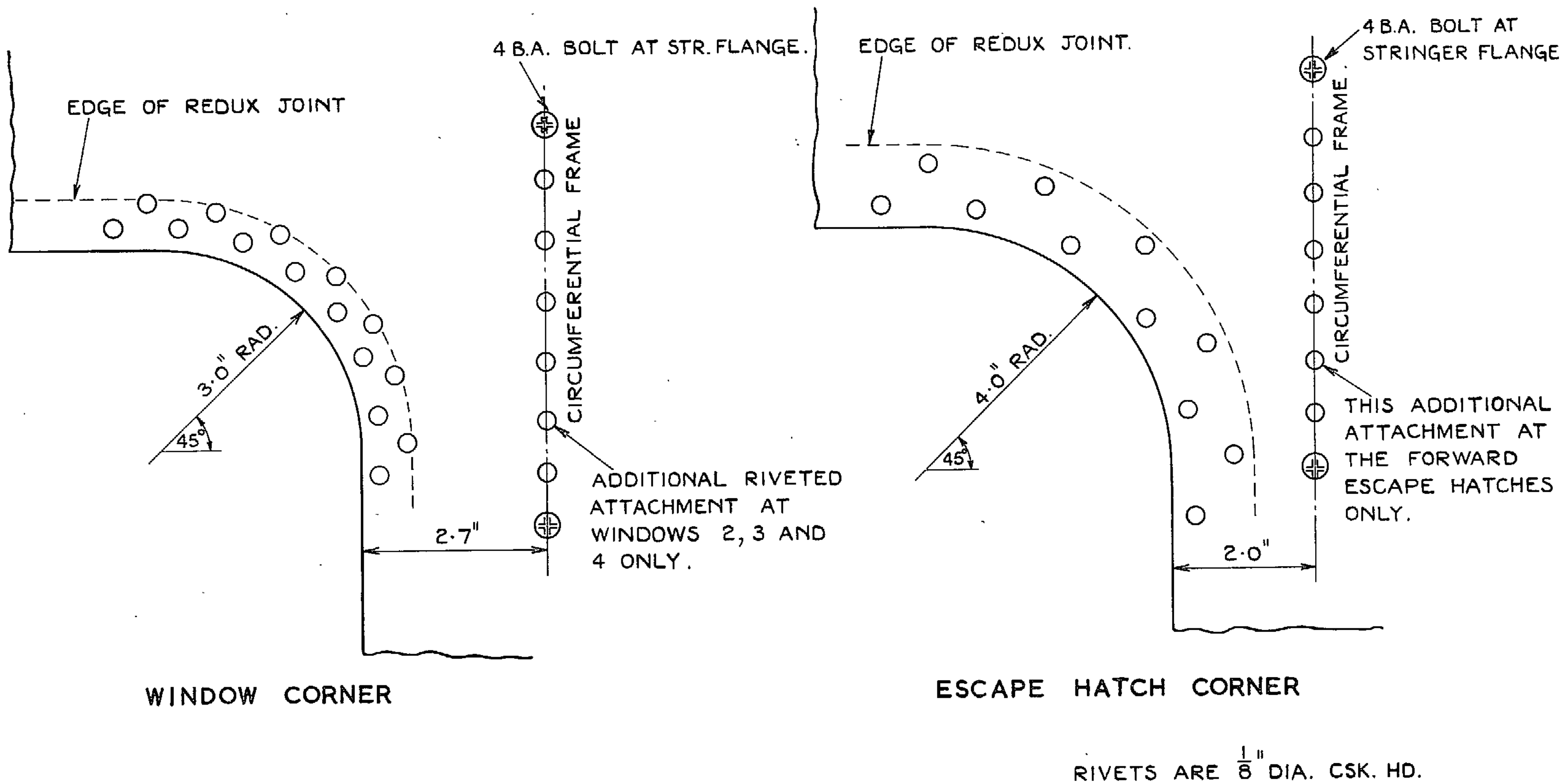


FIG. 9. External structural details at window and escape-hatch-aperture corners.

(8824)

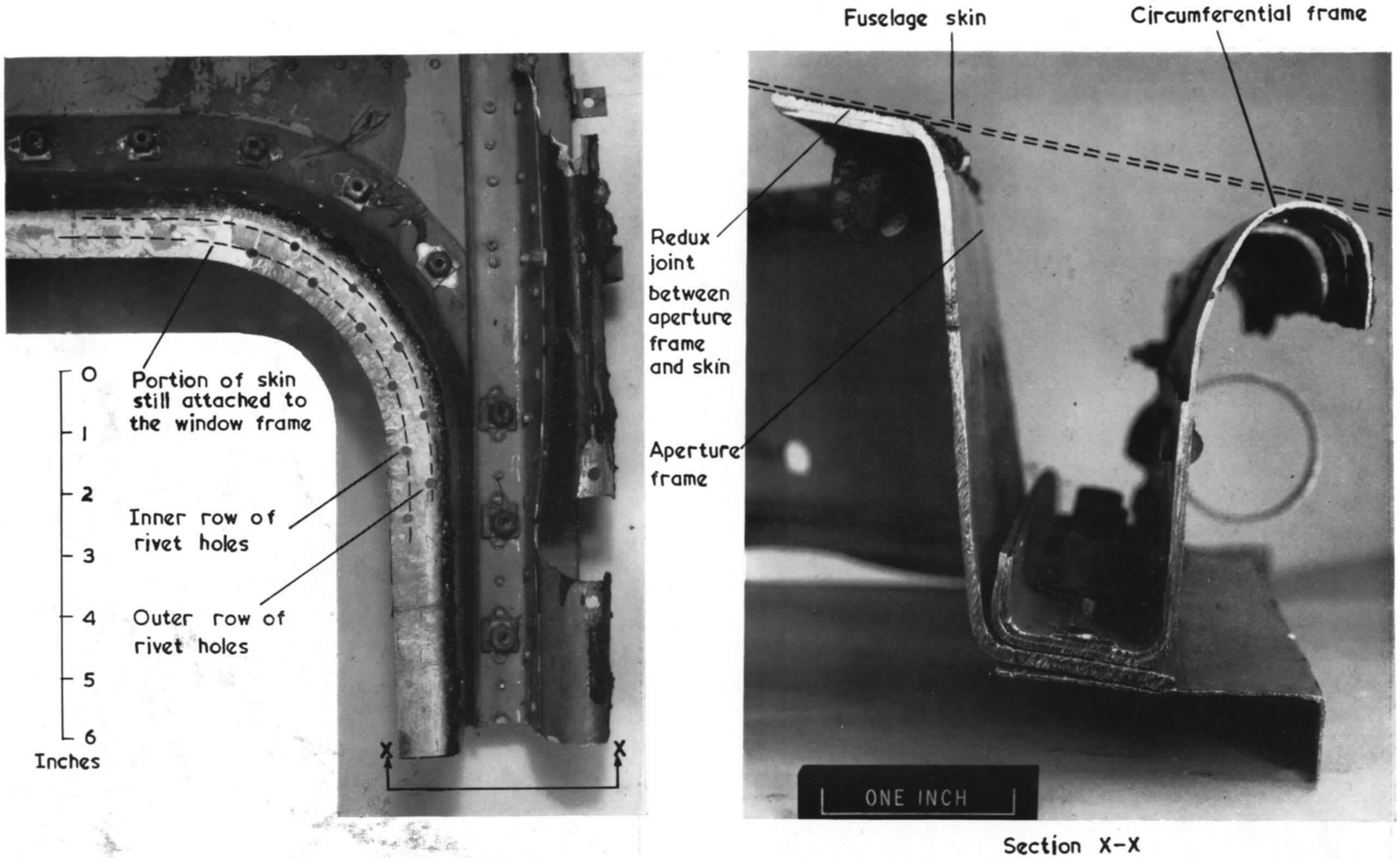


FIG. 10. Local structure at a window corner, viewed from outside with skin removed.

D**

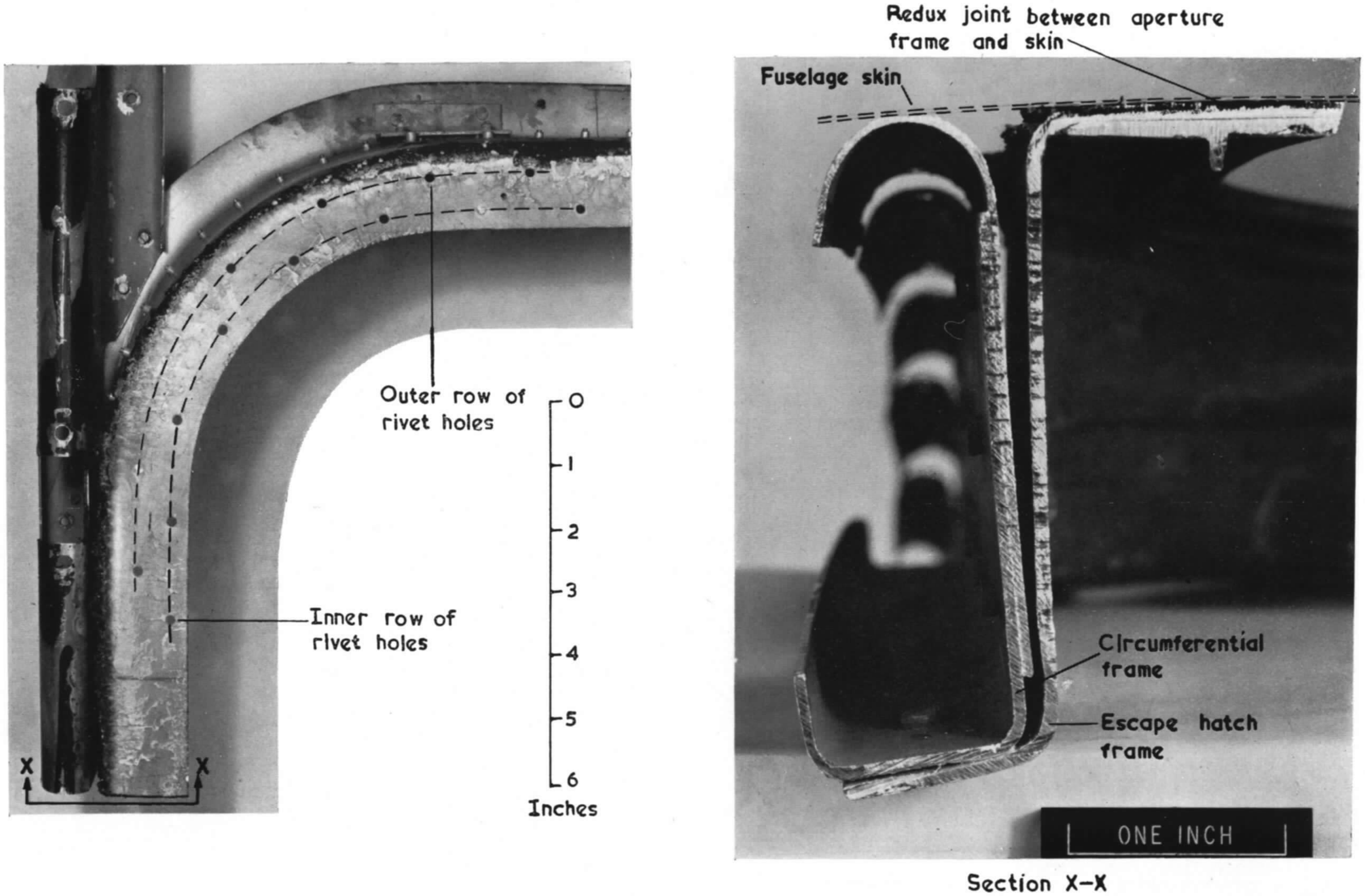


FIG. 11. Local structure at an escape-hatch corner, viewed from outside with skin removed.

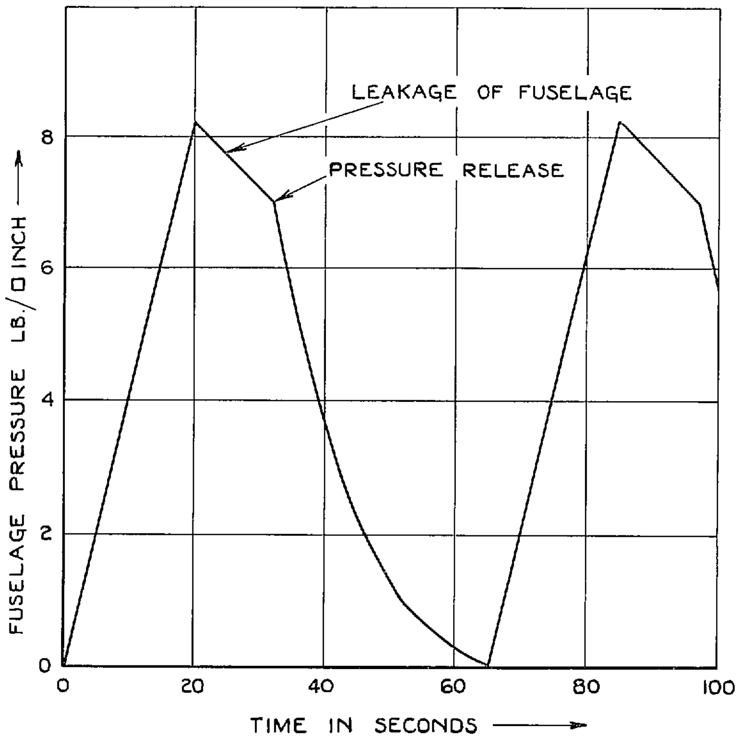


FIG. 12. The pressure cycle.

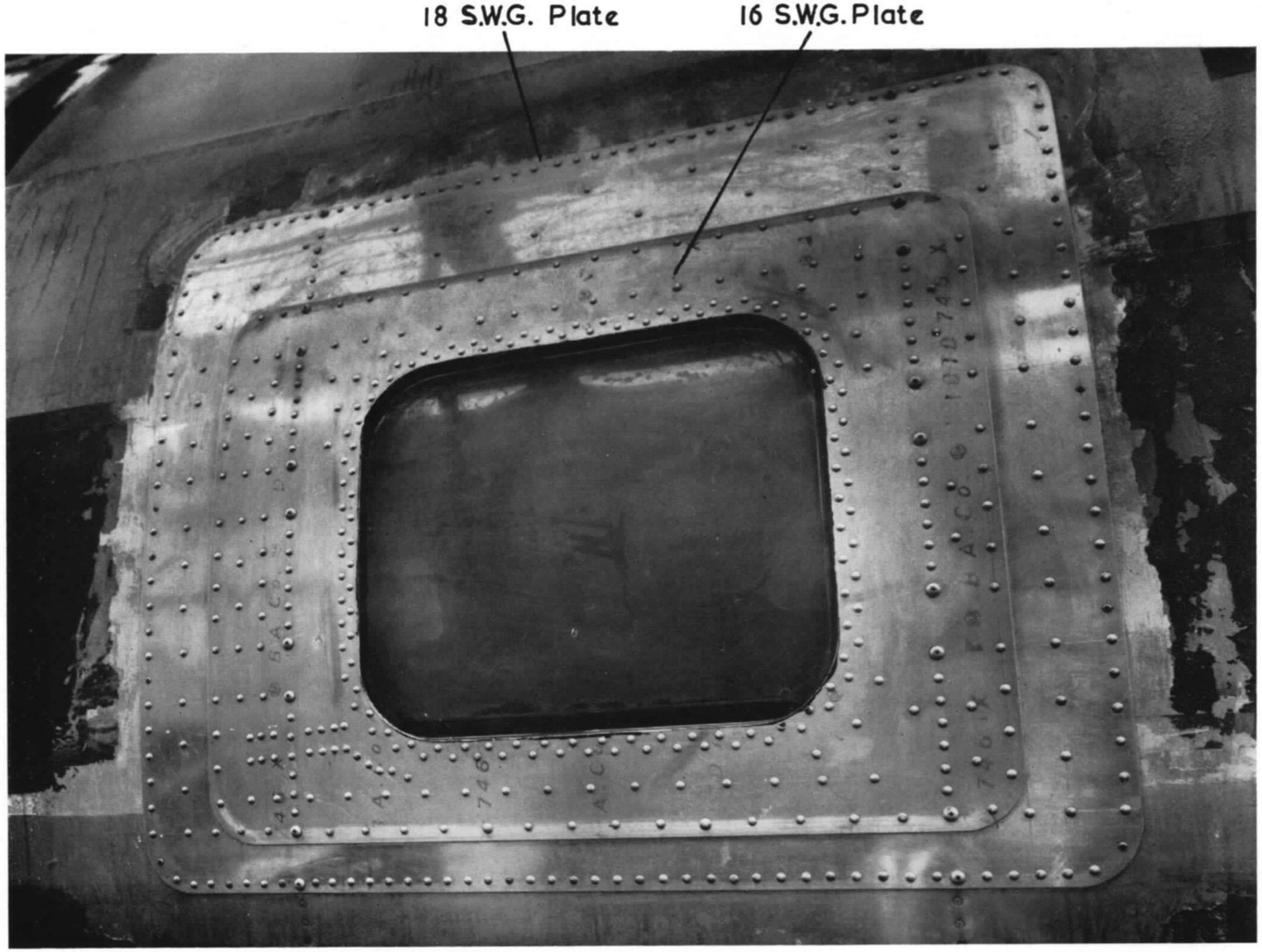


FIG. 13. Typical window repair.

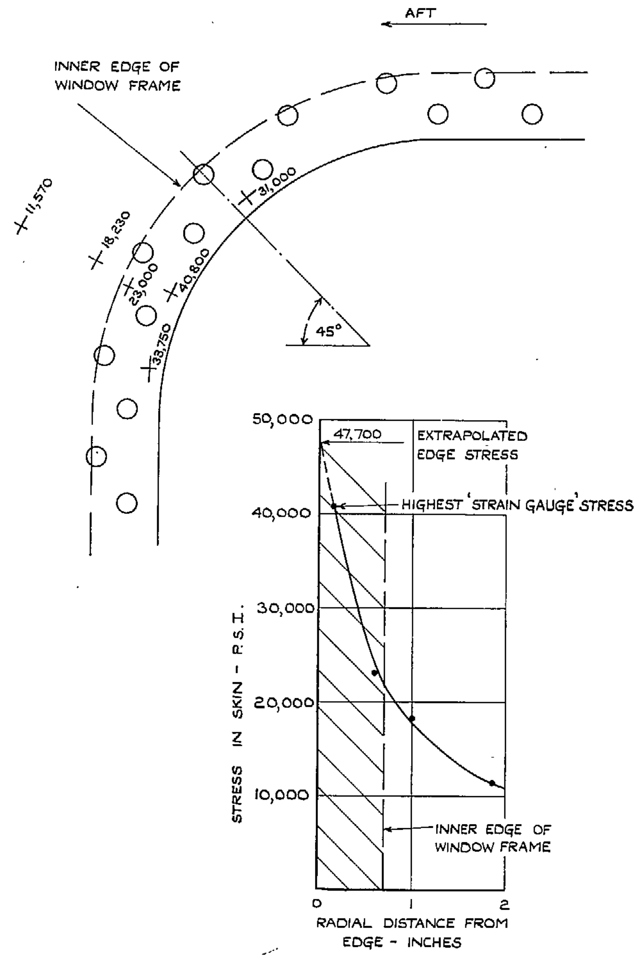


FIG. 14. Stresses in the skin at the top corner of the third starboard window for an internal pressure of 8·25 p.s.i.

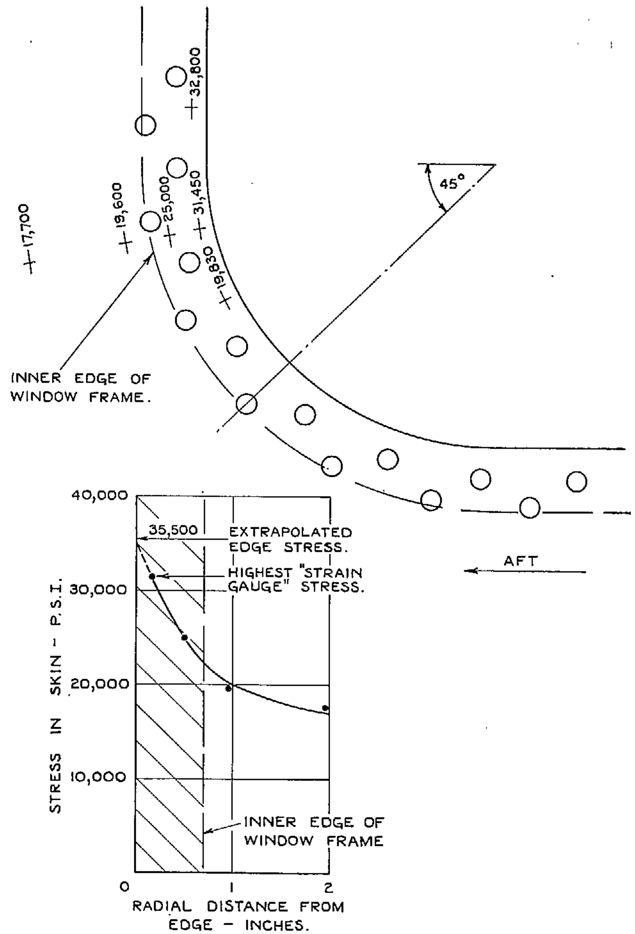


FIG. 15. Stresses in the skin at the bottom corner of the third starboard window for an internal pressure of 8·25 p.s.i.

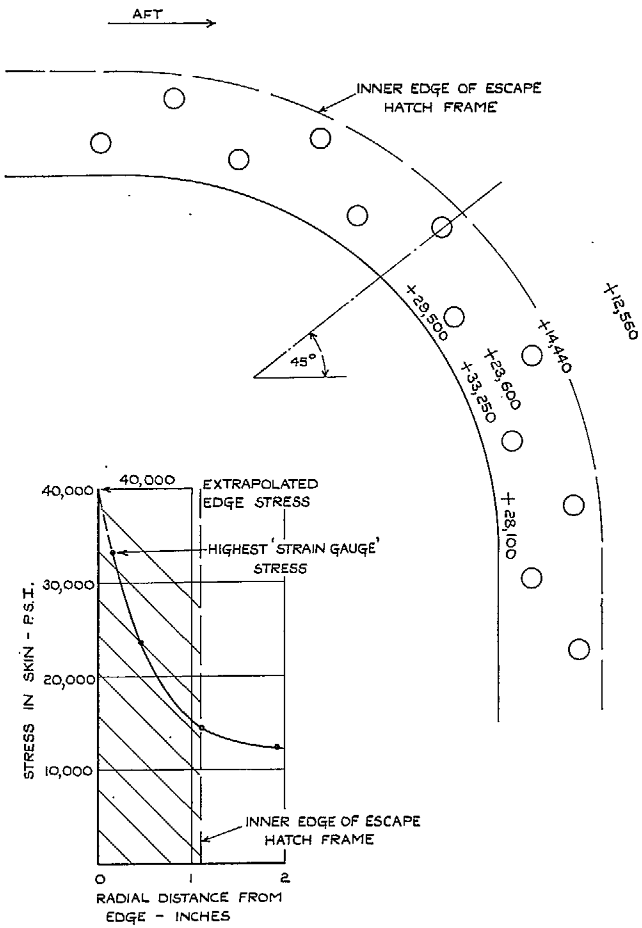


FIG. 16. Stresses in the skin at the top corner of the forward port escape hatch for an internal pressure of 8·25 p.s.i.

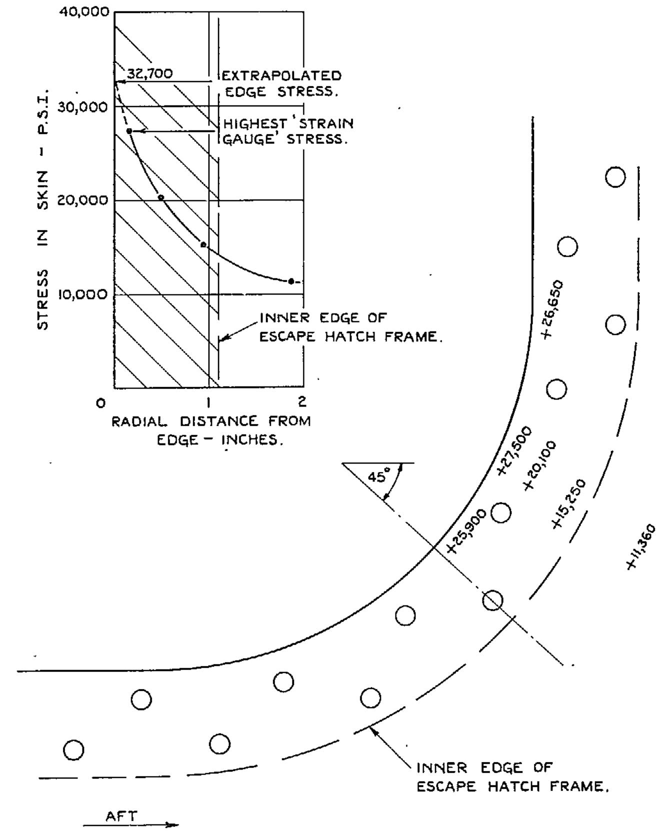


FIG. 17. Stresses in the skin at the bottom corner of the forward port escape hatch for an internal pressure of 8·25 p.s.i.

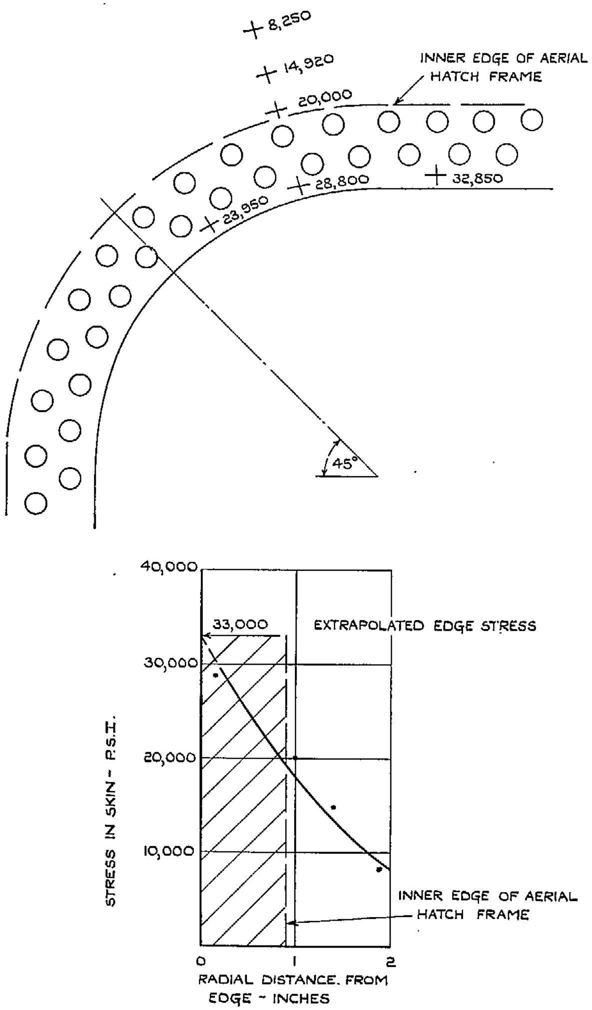


FIG. 18. Stresses in the skin at the port forward corner of the rear aerial hatch.

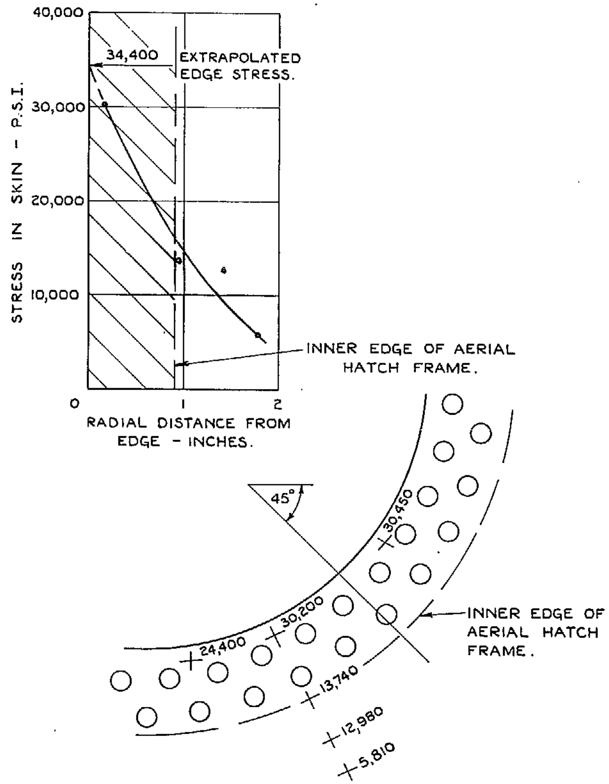
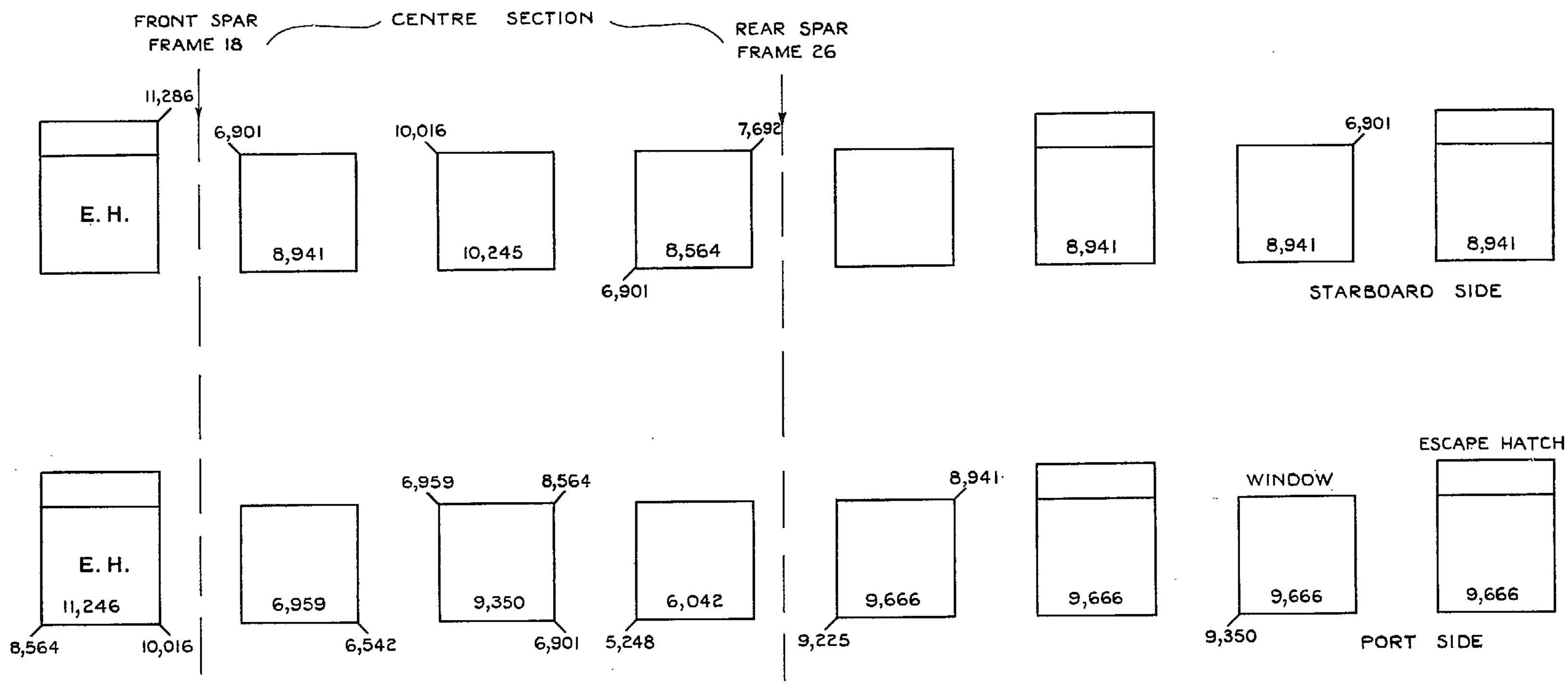


FIG. 19. Stresses in the skin at the starboard rear corner of the rear aerial hatch.



NOTES :–

(1) NUMBERS AT CORNERS ARE THE PRESSURE CYCLES WHEN THE FATIGUE CRACKS WERE FIRST OBSERVED

(2) NUMBERS INSIDE ARE THE PRESSURE CYCLES WHEN THE APERTURE WAS REPAIRED OR REINFORCED AND THEREFORE ELIMINATED FROM THE TEST.

FIG. 20. Distribution of fatigue cracks at window and escape-hatch-aperture corners.

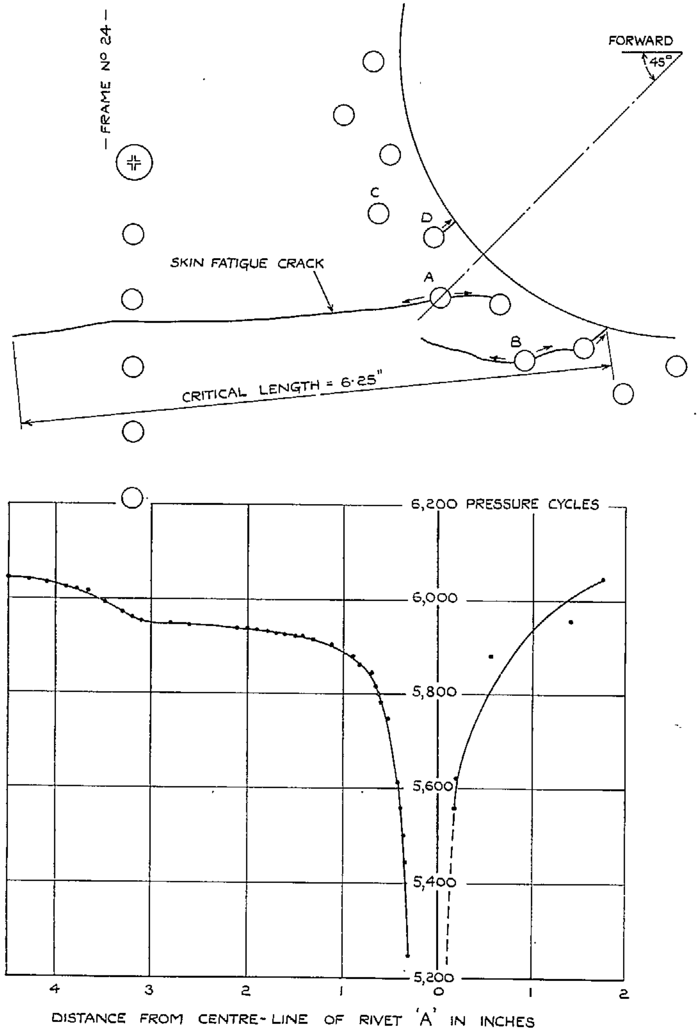


FIG. 21. Crack growth at third window, port side. (Bottom forward corner)

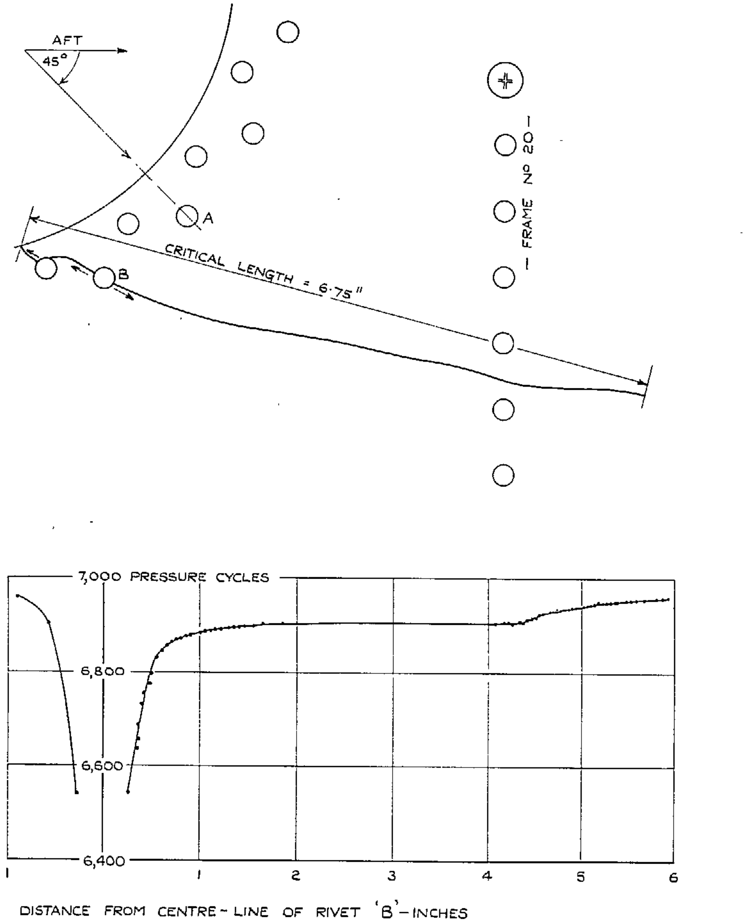


FIG. 22. Crack growth at first window, port side. (Bottom rear corner)

(83824)
E

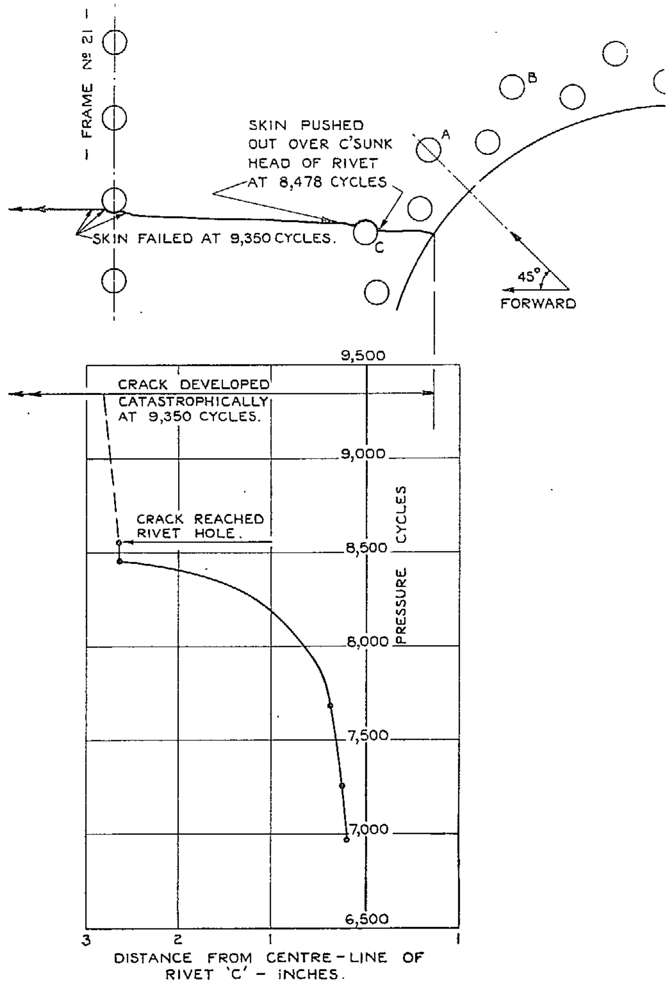


FIG. 23. Crack growth at second window, port side. (Top forward corner)

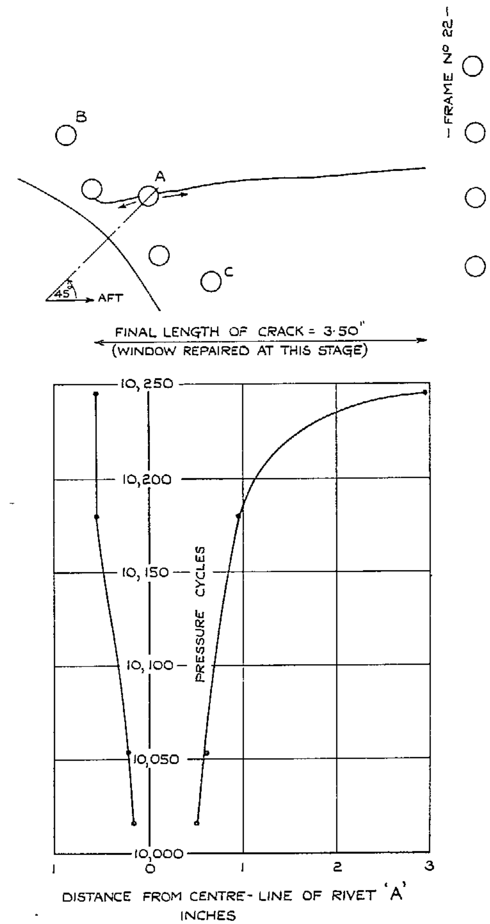


FIG. 24. Crack growth at second window, starboard side. (Top forward corner)

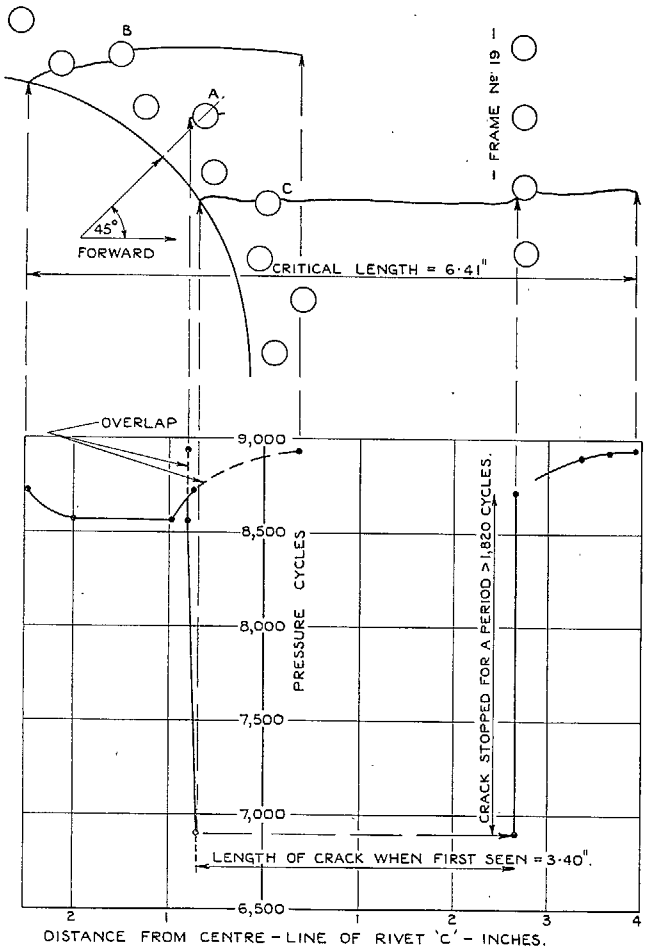


FIG. 25. Crack growth at first window, starboard side. (Top forward corner)

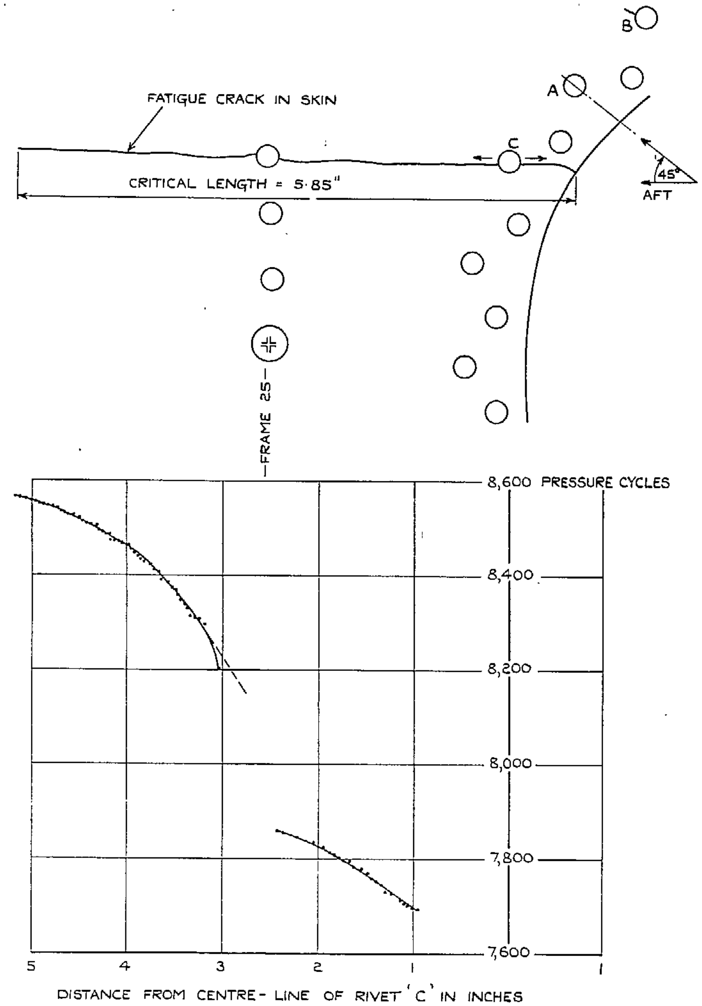


FIG. 26. Crack growth at third window, starboard side. (Top rear corner)

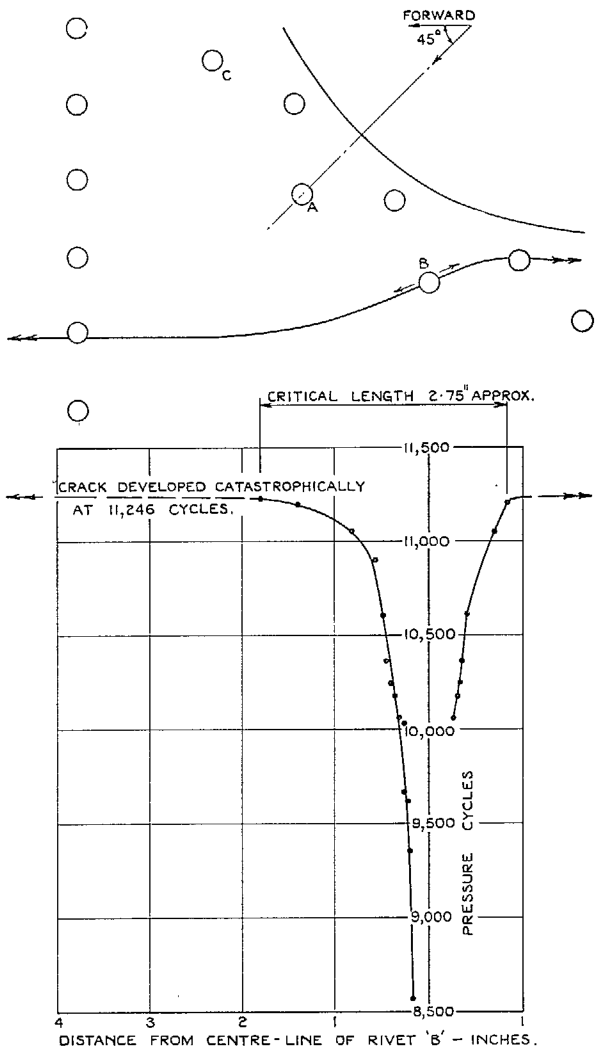


FIG. 27. Crack growth at forward escape hatch, port side. (Bottom forward corner)

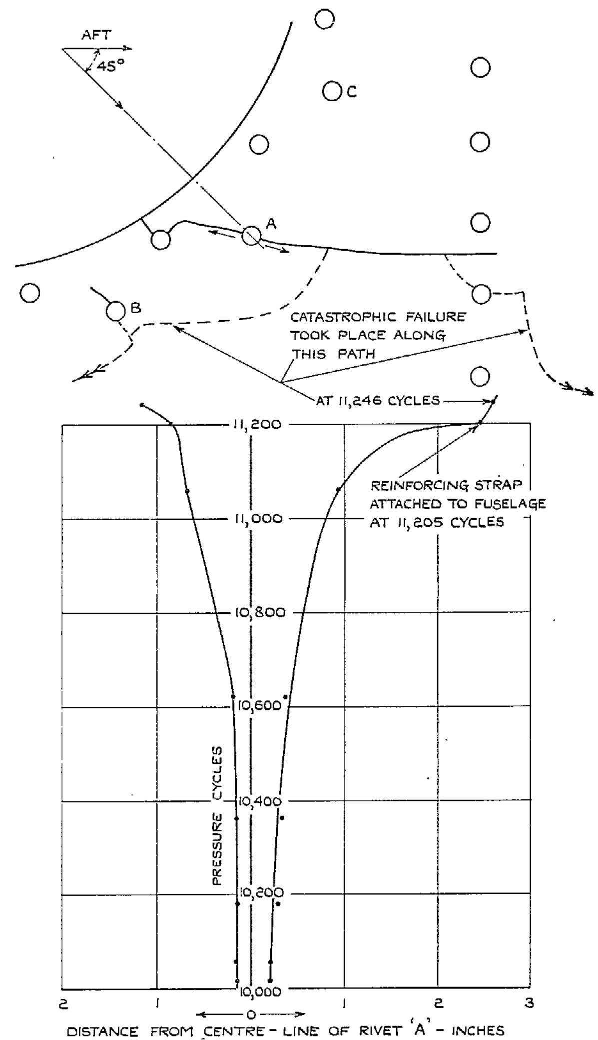


FIG. 28. Crack growth at forward escape hatch, port side. (Bottom rear corner)

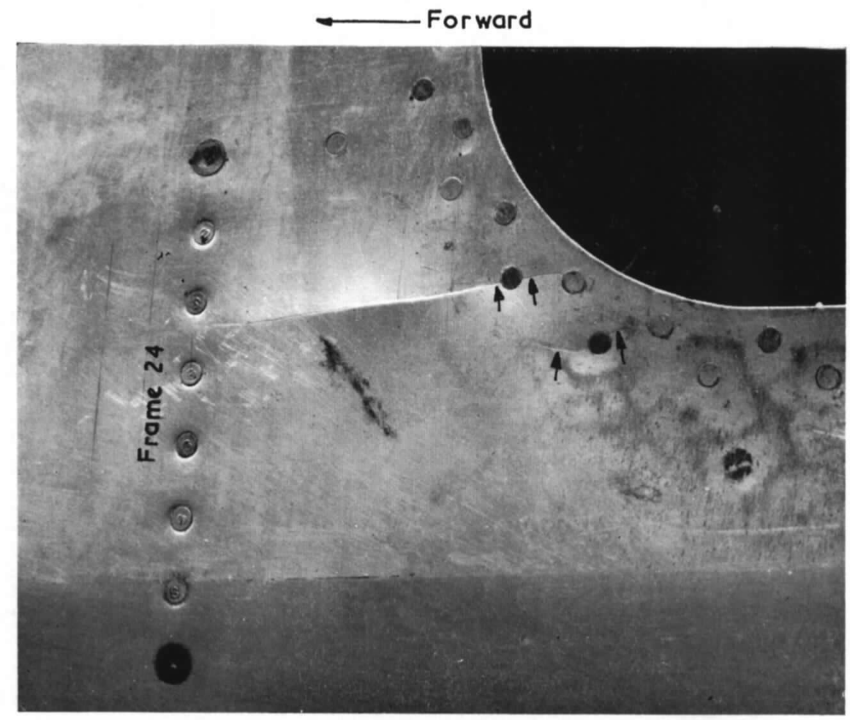


FIG. 31. Third port window corner, 5,951 cycles.

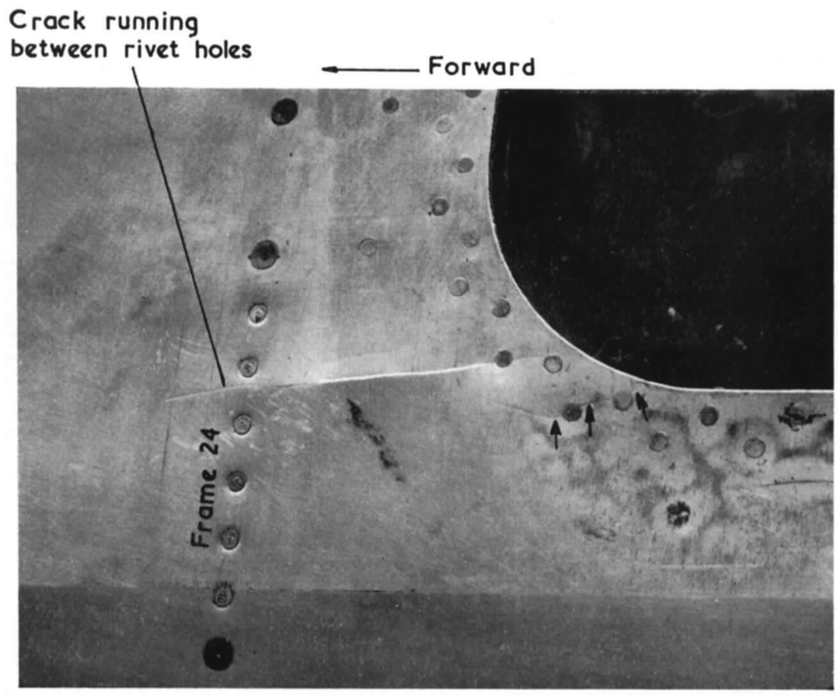


FIG. 32. Third port window corner, 6,042 cycles.

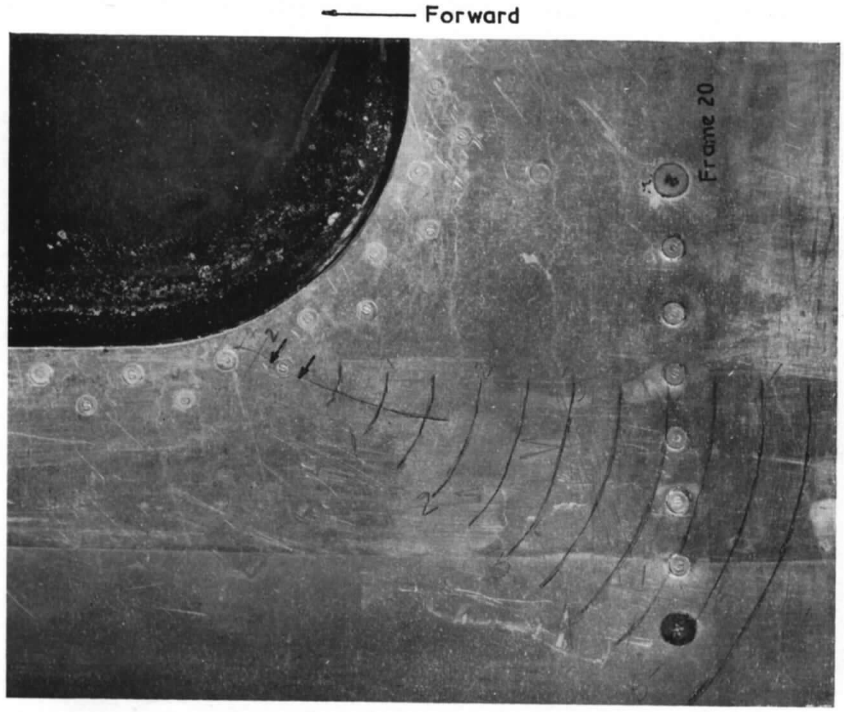


FIG. 33. First port window corner, 6,901 cycles.

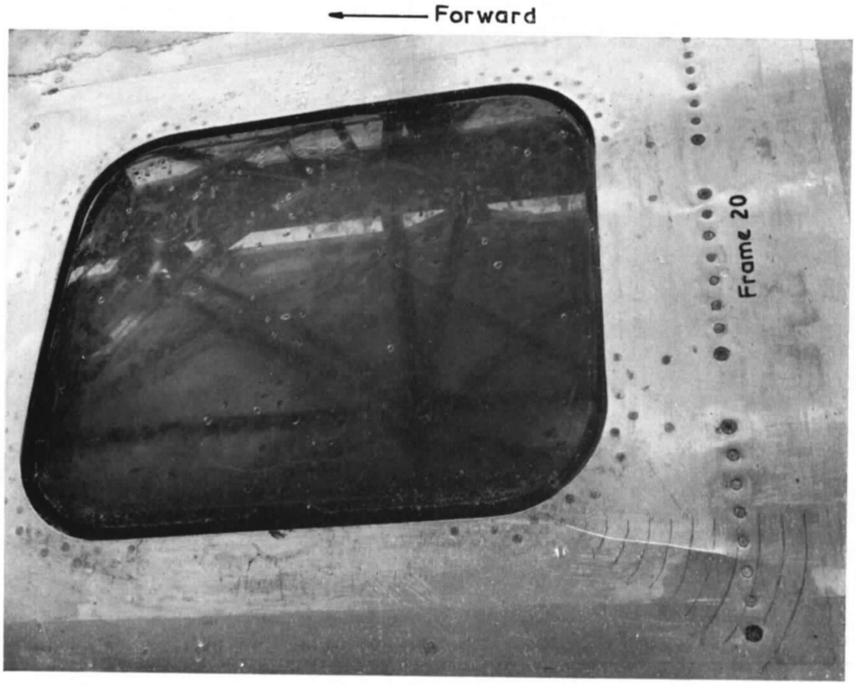


FIG. 34. First port window corner, 6,959 cycles.

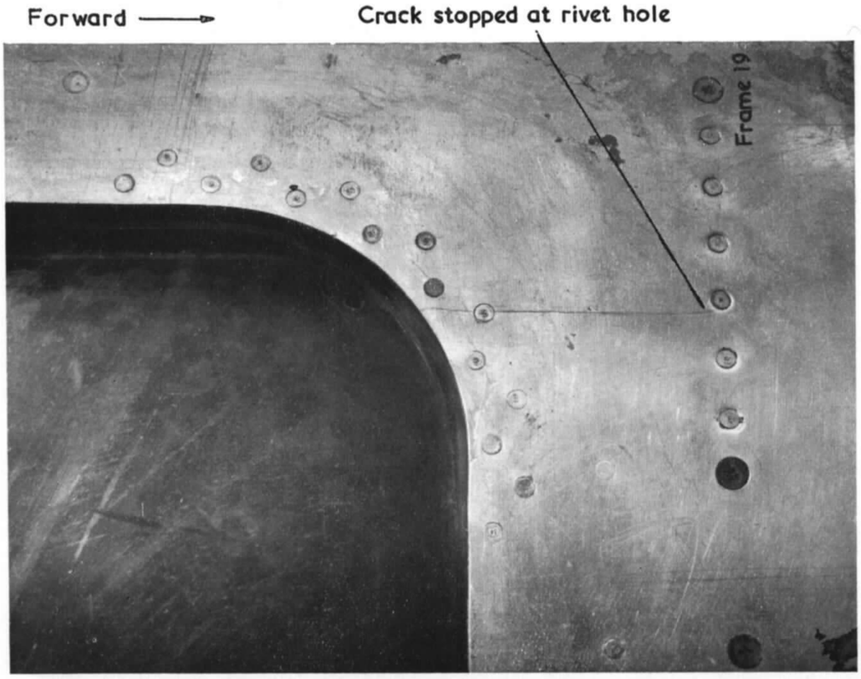


FIG. 35. Crack stopped at rivet hole in frame, 6,901 cycles.
First starboard window.

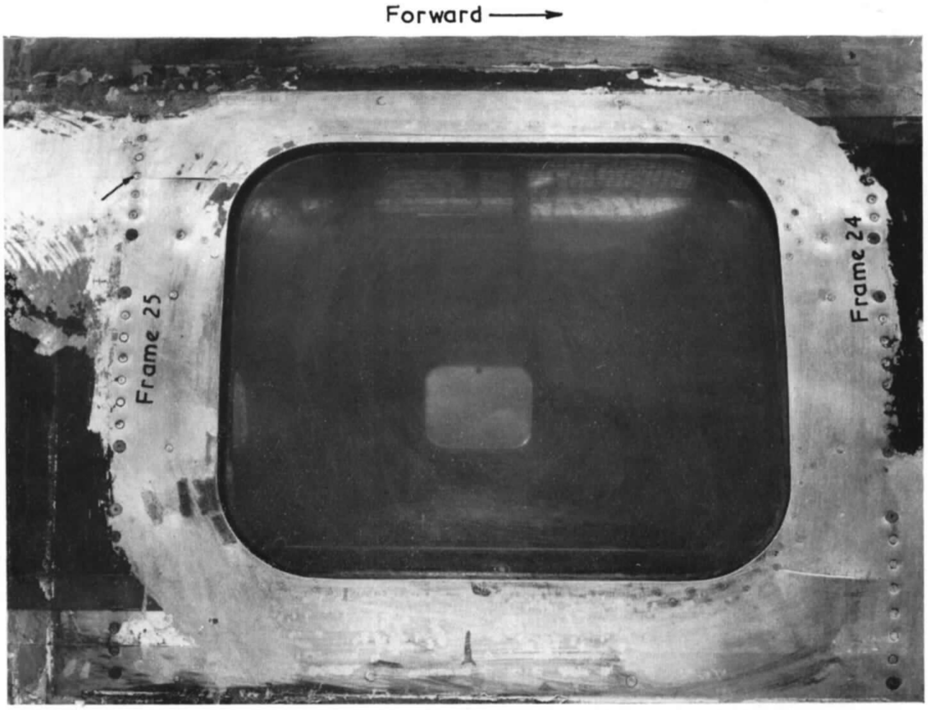


FIG. 36. Cracks stopped at riveted frames, 8,564 cycles.
Third starboard window.

(8824) Wt. 67/1876 K.5 7/62 Hw.

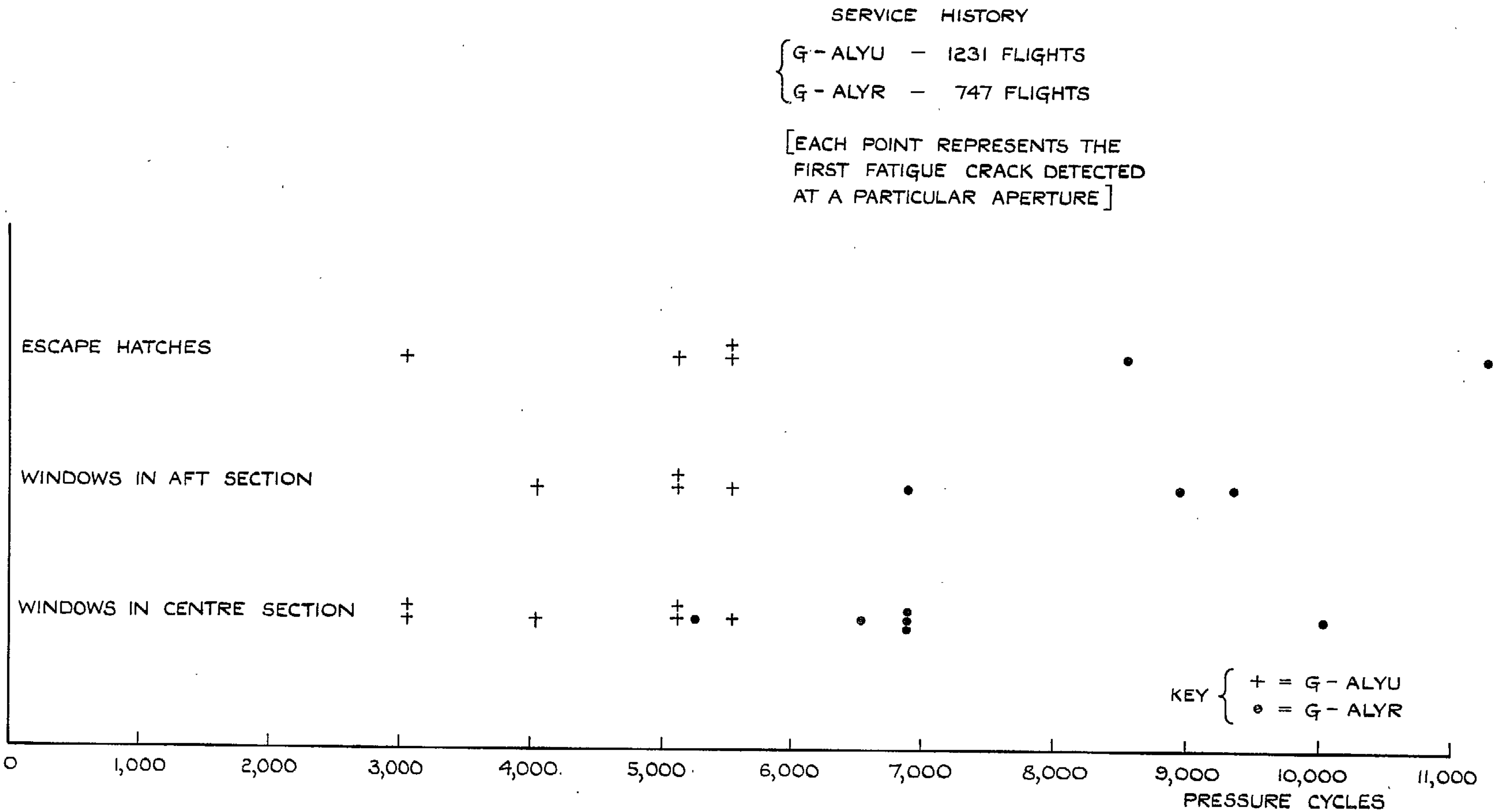


Fig. 37. Distribution of fatigue cracks at apertures.

Publications of the Aeronautical Research Council

ANNUAL TECHNICAL REPORTS OF THE AERONAUTICAL RESEARCH COUNCIL (BOUND VOLUMES)

1942 Vol. I. Aero and Hydrodynamics, Aerofoils, Airscrews, Engines. 75*s.* (post 2*s.* 9*d.*)
Vol. II. Noise, Parachutes, Stability and Control, Structures, Vibration, Wind Tunnels. 47*s.* 6*d.* (post 2*s.* 3*d.*)

1943 Vol. I. Aerodynamics, Aerofoils, Airscrews. 80*s.* (post 2*s.* 6*d.*)
Vol. II. Engines, Flutter, Materials, Parachutes, Performance, Stability and Control, Structures. 90*s.* (post 2*s.* 9*d.*)

1944 Vol. I. Aero and Hydrodynamics, Aerofoils, Aircraft, Airscrews, Controls. 84*s.* (post 3*s.*)
Vol. II. Flutter and Vibration, Materials, Miscellaneous, Navigation, Parachutes, Performance, Plates and Panels, Stability, Structures, Test Equipment, Wind Tunnels. 84*s.* (post 3*s.*)

1945 Vol. I. Aero and Hydrodynamics, Aerofoils. 130*s.* (post 3*s.* 6*d.*)
Vol. II. Aircraft, Airscrews, Controls. 130*s.* (post 3*s.* 6*d.*)
Vol. III. Flutter and Vibration, Instruments, Miscellaneous, Parachutes, Plates and Panels, Propulsion. 130*s.* (post 3*s.* 3*d.*)
Vol. IV. Stability, Structures, Wind Tunnels, Wind Tunnel Technique. 130*s.* (post 3*s.* 3*d.*)

1946 Vol. I. Accidents, Aerodynamics, Aerofoils and Hydrofoils. 168*s.* (post 3*s.* 9*d.*)
Vol. II. Airscrews, Cabin Cooling, Chemical Hazards, Controls, Flames, Flutter, Helicopters, Instruments and Instrumentation, Interference, Jets, Miscellaneous, Parachutes. 168*s.* (post 3*s.* 3*d.*)
Vol. III. Performance, Propulsion, Seaplanes, Stability, Structures, Wind Tunnels. 168*s.* (post 3*s.* 6*d.*)

1947 Vol. I. Aerodynamics, Aerofoils, Aircraft. 168*s.* (post 3*s.* 9*d.*)
Vol. II. Airscrews and Rotors, Controls, Flutter, Materials, Miscellaneous, Parachutes, Propulsion, Seaplanes, Stability, Structures, Take-off and Landing. 168*s.* (post 3*s.* 9*d.*)

1948 Vol. I. Aerodynamics, Aerofoils, Aircraft, Airscrews, Controls, Flutter and Vibration, Helicopters, Instruments, Propulsion, Seaplane, Stability, Structures, Wind Tunnels. 130*s.* (post 3*s.* 3*d.*)
Vol. II. Aerodynamics, Aerofoils, Aircraft, Airscrews, Controls, Flutter and Vibration, Helicopters, Instruments, Propulsion, Seaplane, Stability, Structures, Wind Tunnels. 110*s.* (post 3*s.* 3*d.*)

Special Volumes

Vol. I. Aero and Hydrodynamics, Aerofoils, Controls, Flutter, Kites, Parachutes, Performance, Propulsion, Stability. 126*s.* (post 3*s.*)
Vol. II. Aero and Hydrodynamics, Aerofoils, Airscrews, Controls, Flutter, Materials, Miscellaneous, Parachutes, Propulsion, Stability, Structures. 147*s.* (post 3*s.*)
Vol. III. Aero and Hydrodynamics, Aerofoils, Airscrews, Controls, Flutter, Kites, Miscellaneous, Parachutes, Propulsion, Seaplanes, Stability, Structures, Test Equipment. 189*s.* (post 3*s.* 9*d.*)

Reviews of the Aeronautical Research Council

1939–48 3*s.* (post 6*d.*) 1949–54 5*s.* (post 5*d.*)

Index to all Reports and Memoranda published in the Annual Technical Reports

1909–1947 R. & M. 2600 (out of print)

Indexes to the Reports and Memoranda of the Aeronautical Research Council

Between Nos. 2351–2449	R. & M. No. 2450	2*s.* (post 3*d.*)
Between Nos. 2451–2549	R. & M. No. 2550	2*s.* 6*d.* (post 3*d.*)
Between Nos. 2551–2649	R. & M. No. 2650	2*s.* 6*d.* (post 3*d.*)
Between Nos. 2651–2749	R. & M. No. 2750	2*s.* 6*d.* (post 3*d.*)
Between Nos. 2751–2849	R. & M. No. 2850	2*s.* 6*d.* (post 3*d.*)
Between Nos. 2851–2949	R. & M. No. 2950	3*s.* (post 3*d.*)
Between Nos. 2951–3049	R. & M. No. 3050	3*s.* 6*d.* (post 3*d.*)
Between Nos. 3051–3149	R. & M. No. 3150	3*s.* 6*d.* (post 3*d.*)

HER MAJESTY'S STATIONERY OFFICE

from the addresses overleaf

Printed and published by
HER MAJESTY'S STATIONERY OFFICE

To be purchased from
York House, Kingsway, London W.C.2
423 Oxford Street, London W.1
13A Castle Street, Edinburgh 2
109 St. Mary Street, Cardiff
39 King Street, Manchester 2
50 Fairfax Street, Bristol 1
35 Smallbrook, Ringway, Birmingham 5
80 Chichester Street, Belfast 1
or through any bookseller

Printed in England

R. & M. No. 3248

S.O. Code No. 23-3248