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An Experimental Verification of the Theoretical Conclusions of R.A.E. Technical Note No. Structures 156 (A.R.C., C.P. No. 286) "A Constructional method for minimising the Hazard of Catastrophic failure in a Pressure Cabin" with further comments on its implications

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An experimental verification of the theoretical conclusions of R.A.E. Technical Note No. Structures 156 (A.R.C., C.P. No.286)

- "A constructional method for minimising the hazard of catastrophic failure in a pressure cabin" - with further comments on its implications

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D. Williams, D.Sc., M.I.Mech.E., F.R.Ae.S.

SUMMARY

In a recent paper[1] the author described a method of construction intended to make the shell of a pressure cabin immune from catastrophic failure at little or no cost in extra weight. The present note records the results of experiments carried out on a Comet I cabin that was modified to incorporate the new constructional method. These experiments, which include some very searching tests, amply confirm the benefits indicated by theory, and appear fully to vindicate the new method of construction.

The note also touches on the momentous implications that arise once this type of construction is accepted as meeting the claims made for it.

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1 Introduction

In the report referred to in the above title the writer outlined a scheme of construction for pressure-cabins which aimed at making them safe from catastrophic failure without paying any appreciable weight penalty. Experimental results are now available that confirm the views put forward in that report and that go a long way towards establishing the scheme as a practical proposition.

2 Brief description of new construction

Before a discussion of the experimental results a brief description of the proposed scheme[1] and its implications may be useful.

In a recent investigation of pressure-cabin structural problems[2], consideration of the effect of transverse frames, bulkheads and former rings on the stresses in the adjacent skin showed that the magnitude of these stresses is highly dependent on the distance from the constraining transverse members.

It was found for example that, if the frames or rings are pitched more than about 20 ins. apart (for a 10 ft diameter cabin with conventional stringer reinforcement), the skin midway between a pair of adjacent rings is, so to speak, unaware of their constricting effect, with the result that its radial expansion under pressure is unaffected. This means that the relief from hoop tension enjoyed by the skin close to the rings is not shared by the skin midway between them, which suffers much the same hoop stress as it would in the absence of the rings. The picture is completely different when the pitch of the rings is reduced to something like 10 ins. for then, by virtue of the bending stiffness of the bridging stringers, the radial expansion (and hence the hoop stresses) at, and midway between, frames is practically the same.

This constitutes a fundamental change in the situation, because it means that material put into the rings is almost equally effective in reducing the maximum hoop stress in the skin as material used to increase the thickness of the skin itself. This suggests the idea that hoop tension may advantageously be resisted, not by the skin alone, but by a combination of skin and narrow hoops pitched 10 ins. apart over the whole length of the cabin. If, for example, in the conventional type of construction, a skin thickness of 0.044 in. were thought to be appropriate, the new scheme would allocate 0.024 in. (say) for the skin proper and the remaining 0.02 towards providing hoops of cross-sectional area 0.2 in^2 pitched 10 in. apart. A certain amount of discretion can naturally be exercised in choosing what proportion of material goes into skin and what goes into hoops, but there should be enough material in the hoops to enable them to withstand the cabin hoop-tension on their own without inducing a hoop stress greater than about half the static ultimate. This condition is approximately satisfied by the relative amounts of material in skin and hoops in the cabin specimen here considered.

The merit of using a skin-hoop combination in preference to all-skin (assuming the skin stress to be the same in each case) rests on the fact that, whereas a skin crack in the combination structure stands a chance, amounting to practically 100% certainty, of being stopped by the nearest hoop, a similar crack in the all-skin construction may, unless spotted in time, propagate catastrophically.

One is, indeed, justified in concluding that, in the matter of cabin safety, the new construction offers a degree of safety that is not approached by the conventional construction, and offers it moreover at practically no extra cost in weight. Indeed, the new construction should result in substantial weight-saving since, once safety is assured, there is no longer any need to rely on the highly uneconomic policy of using thicker skin as an insurance against the occurrence of catastrophic failure in what is deemed to be the safe life of the aircraft.

3 Implications of new construction in relation to 'safe' life

If this conclusion is accepted - and the experimental evidence seems to support it - certain far-reaching implications need to be mentioned. Foremost among these is the attitude one should adopt to the notion of stipulating a safe life for a pressure-cabin. Whatever the chosen span of life may be - whether 30,000 or 50,000 hours - its termination is, according to present notions, to be the signal for taking the aircraft out of service irrespective of its structural condition.

That condition ought to be excellent because, on the basis of this scheme, a 'safe' life is a crack-free life. This means that an aircraft that, to all appearance, is sound and serviceable has to be scrapped for fear that a crack developed at this stage of its fatigue life might lead to catastrophic failure. In all probability the aircraft would give first-rate service for another 30,000 hours or even more. For it must be remembered that the 'safe' life has to be based on a single test which, because of the wide scatter in fatigue-test results, must indicate a life-span five or ten times greater than the 'safe' life aimed at.

The single test that provides the basis for estimating the 'safe' life is itself a major undertaking, the bypassing of which would save a great deal of time and money. Not that it would be desirable in the immediate future to dispense with the water-tank test, for, even with the new type of construction, the tank test still performs a valuable function, first by demonstrating that the new construction does indeed justify the claims made for it, secondly by indicating any weak points in the cabin design, and thirdly by providing a rough estimate of the fatigue behaviour of the cabin under progressive load repetitions. The main point is that the test, although useful, need no longer be obligatory.

By the adoption of the skin-hoop type of construction it becomes unnecessary any more to gamble on a 'safe' life. Instead, the cabin will be used until either the wings give trouble or deterioration of the cabin makes its continued repair an uneconomic proposition.

4 Test results

The R.A.E. tests were carried out on a Comet I fuselage which had already been subjected to a great number of varied fatigue tests in the R.A.E. tank. Since the hoops (or bands) were located on the outside of the pressure-cabin, it was a comparatively easy matter to fit them. Some were fitted at the recommended pitch of 10 in. and others at 16 in. and 21 in.; some were fastened to the skin with a single line of rivets and some were attached with Araldite cement as well as rivets.

The procedure was to introduce an artificial longitudinal crack in the form of a 3 or 5 in. saw-cut (0.02" wide) in the skin. Each cycle of operations consisted of raising the internal hydraulic pressure up to $8\frac{1}{2}$ lb/in.^{2} above atmospheric and lowering it again. As the crack spread the number of cycles was noted at each stage.

In the absence of the hoops the above pressure represents a skin hoop-stress of 18,000 lb/in.^{2}. The hoops, 1.2" wide by 0.128" thick, when pitched 10.5" apart represent an amount of material equivalent to an extra 0.0146" of skin. Adding this to the 0.028" skin of the Comet I thus makes a total of 0.0426" effective thickness. The adding of the hoops may be regarded as an alternative way of introducing extra material to that used by De Havillands on the Comet IV where the skin thickness is 0.04 (19 s.w.g.).

4.1 1st test

The arrangement of the stringers and hoops in relation to the saw-cut is shown diagrammatically in Fig.1.

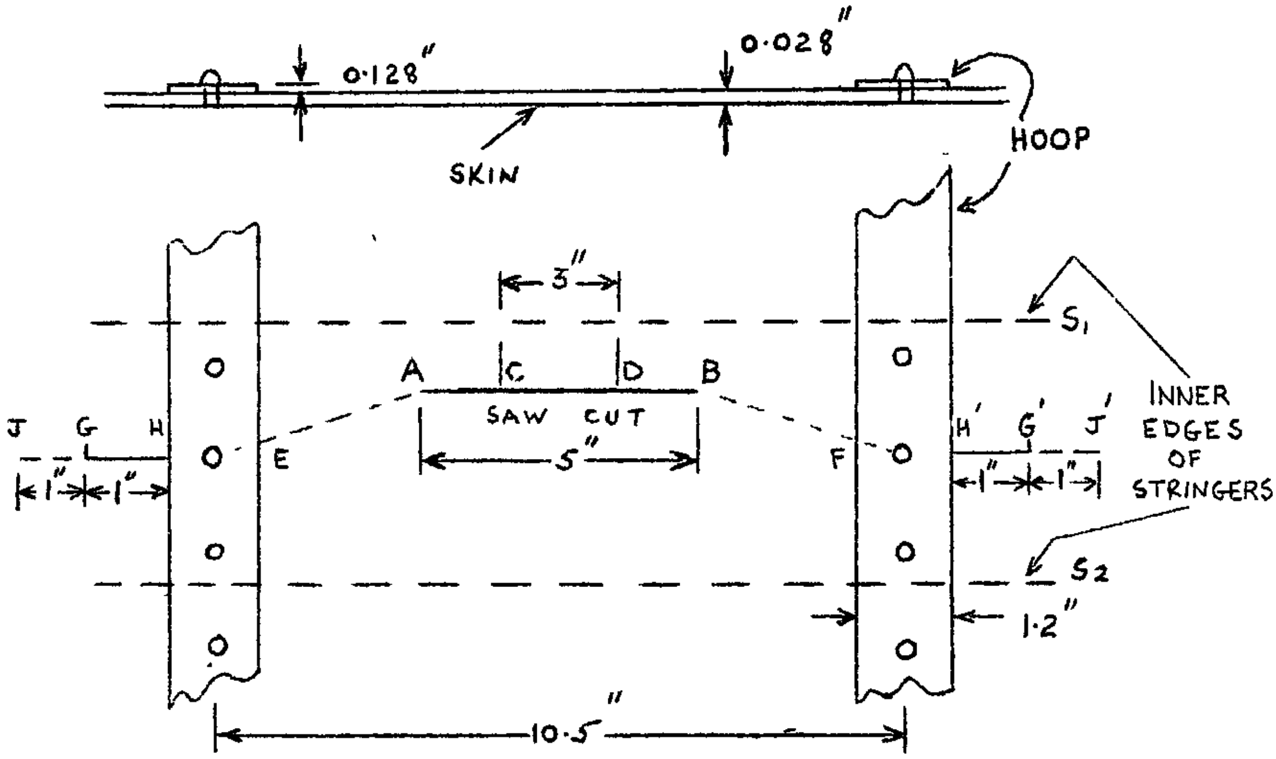

Fig.1 - Hoops fastened by rivets alone

CD represents the initial saw-cut 3 in. long between the stringers S_1 and S_2. Further saw-cuts were made in accordance with the following record which relates crack propagation to number of load repetitions.

Number of repetitions	Remarks
40	No spontaneous extension of crack. Saw-cut extended to 3.5 in.
120	Crack extended to 4 in. Saw-cut to 5 in.
250	Crack gradually reached hoops at E and F. Fresh saw-cuts 1 in. long at GH and G'H'.
1400	Crack slowly extended about 1 in. to J and J'.

4.2 2nd test

In the 2nd test the hoops were attached by Araldite cement as well as rivets. Moreover a full 5 in. saw-cut was made at the start, extending from close to the left-hand hoop (Fig.2).

/Fig.2

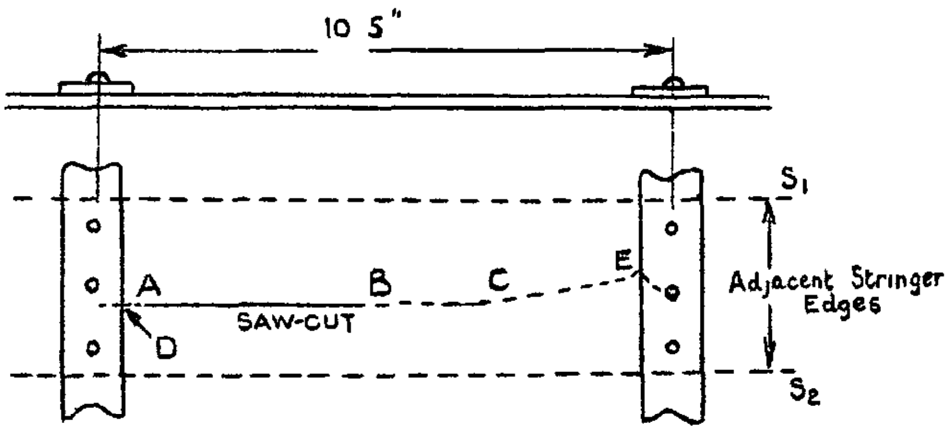

Fig. 2 - Hoops fastened by rivets plus Araldite

Number of repetitions	Remarks
200	Crack gradually spread to C and D.
300	Crack reached edge of hoop at E.
1400	Crack spread some distance under hoop, towards a rivet on the right-hand and in between two rivets on the left, but without spreading into adjacent bays.

4.3 3rd test

In this test the effect was tried of drastically saw-cutting through skin and hoops while the pressure was actually on, in order to see how far the structure could tolerate this kind of treatment before finally disrupting. The following table records what happened in relation to Fig.3.

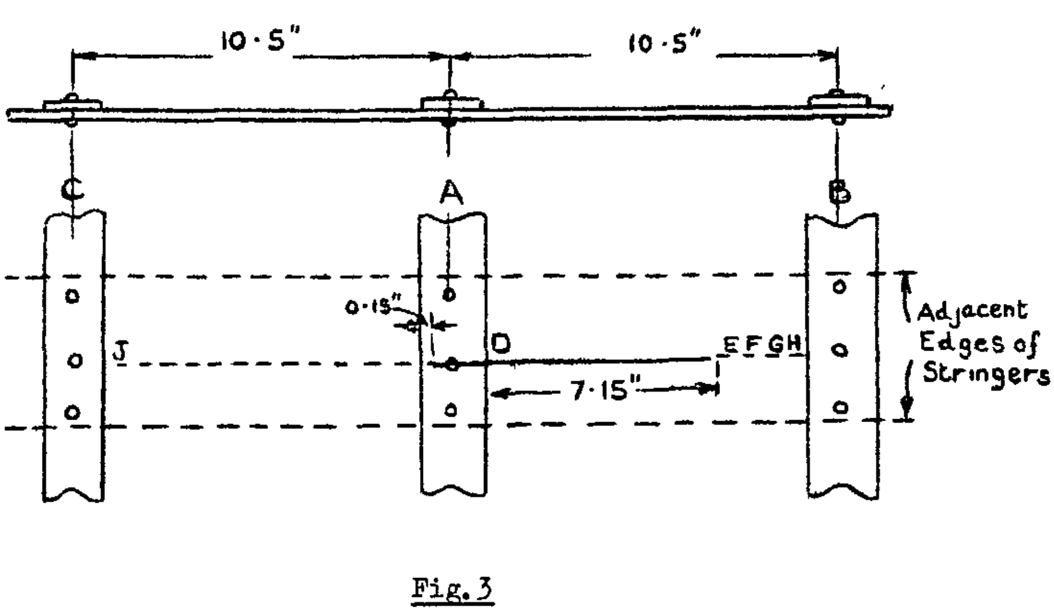

Fig. 3

Number of repetitions	Remarks
0	A 6.75 in. saw-cut D.E. was made, extending from edge D of hoop A to point E.
1st cycle	With 8.25 lb/in.^{2} pressure maintained, skin and hoop A saw-cut from D to half way across hoop. On release of pressure no extension of cut noticed. Saw-cut in skin extended to F.
2nd cycle	With pressure maintained, saw-cut in hoop A (and associated skin) extended so that only 0.15 in (out of the original 1.2 in.) remained intact. On release, crack at F had extended 0.95 in. to G.
3rd cycle	Crack at G extended to H, 0.2 in. from edge of hoop B.
After 5 cycles	Hoop A still holding. Crack at H further extended to edge of hoop B.
After 10 cycles	Failure of remaining 0.15 in. of hoop A resulted in crack shooting across to edge of hoop C at J.
11th cycle	With gap now extending from inner edge of hoop B to inner edge of hoop C, and with pressure fully maintained, hoop B was slowly sawn through. Nothing happened till hoop was sawn half way through, when catastrophic extension of crack occurred at both ends.

4.4 4th test

This test was done at a hoop pitch of 16 in. The hoop-tension stress in the skin is now much increased because of the reduced amount of material in the hoops per unit length of cabin and of the increased pitch which allows more radial swelling in between hoops. This arrangement is contrary to the recommended practice of specifying a 10 in. (approximate) pitch, but nevertheless constitutes an interesting test.

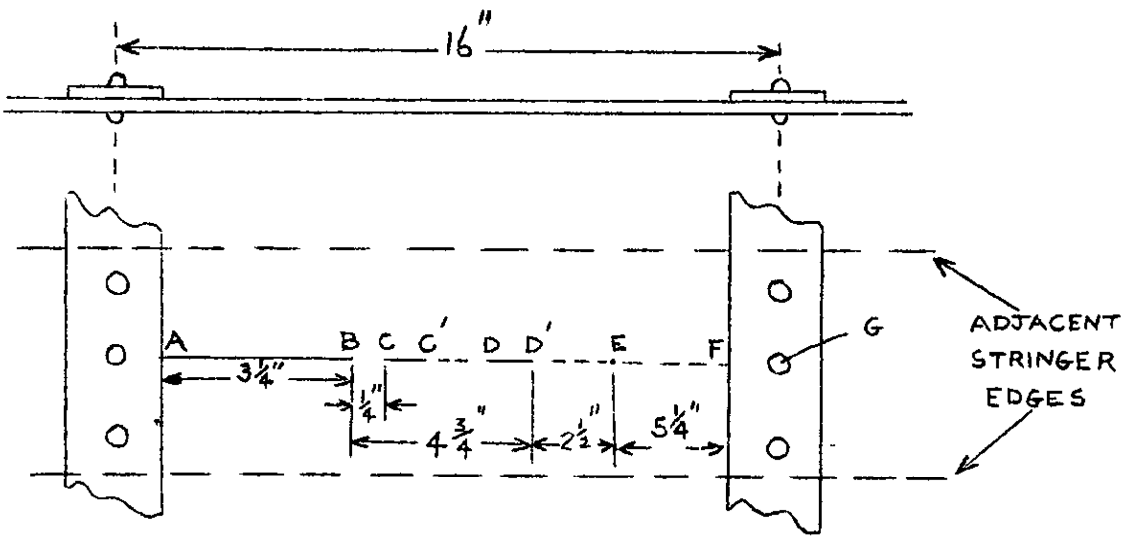

Fig.4 - Hoops attached by rivets alone

A $3\frac{1}{4}$ in. saw-cut AB was made butting right up to the l.h.s. hoop as shown in Fig.4. After 35 cycles crack reached, C, when a further $\frac{1}{4}$" saw-cut CC' was made.

After 75 cycles crack reached D and a further $\frac{1}{2}$" saw-cut DD' was made

" 125 " crack reached E when it suddenly ran across to F

" 150 " skin crack reached rivet G, (but no damage to the hoop).

4.5 5th test

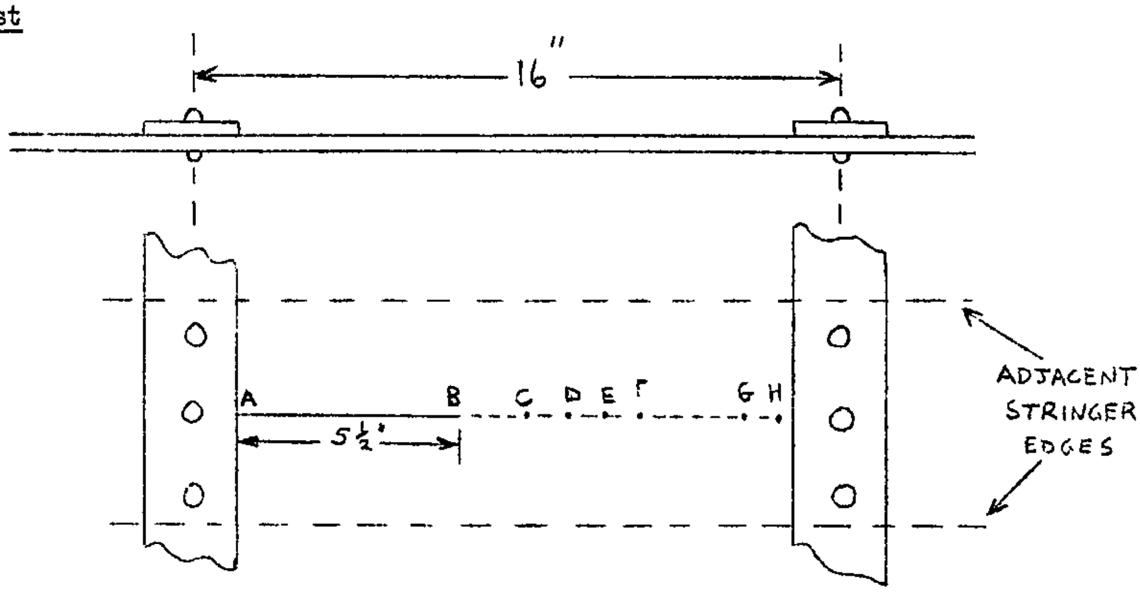

Fig.5 - Hoops attached by rivets and Araldite

This test repeats the 4th test except that the hoops are now attached to the skin by Araldite adhesive in addition to rivets. The record of events is as follows. (Fig.5)

Number of Repetitions of load	Remarks
0	Slot AB, $5\frac{1}{2}$ in. long cut in skin.
30	Crack BC 0.9 in. long formed at end of saw-cut.
70	Crack extended to D making AD 7.05 in., and growing rapidly.
During 77th cycle	Slot-plus-crack extended from E, 8.65 in. from A to F, 11.6 in. from A in the one cycle.
During 78th cycle	Slot-plus-crack extended to G making AG 14.2 in.
After 81st cycle	Crack extended a further 0.75 in. to H making AH 14.95 in. Crack stopped when 0.05 in. from edge of hoop.

4.6 6th test

In this test, as a check on the capacity of a hoop for bringing a fast running crack to a halt, the pitch was increased to 21 in. The hoops are in this case too far apart to provide full support to the skin against radial expansion and the skin stress accordingly approaches about half way to the stress it would have in the absence of hoops. Even so the initial $3\frac{1}{2}$ in. saw-cut AB (Fig.6) had to be extended by 3 in. more to C before the crack was disposed to spread. It reached D after 21 cycles and then shot across to E where it stopped.

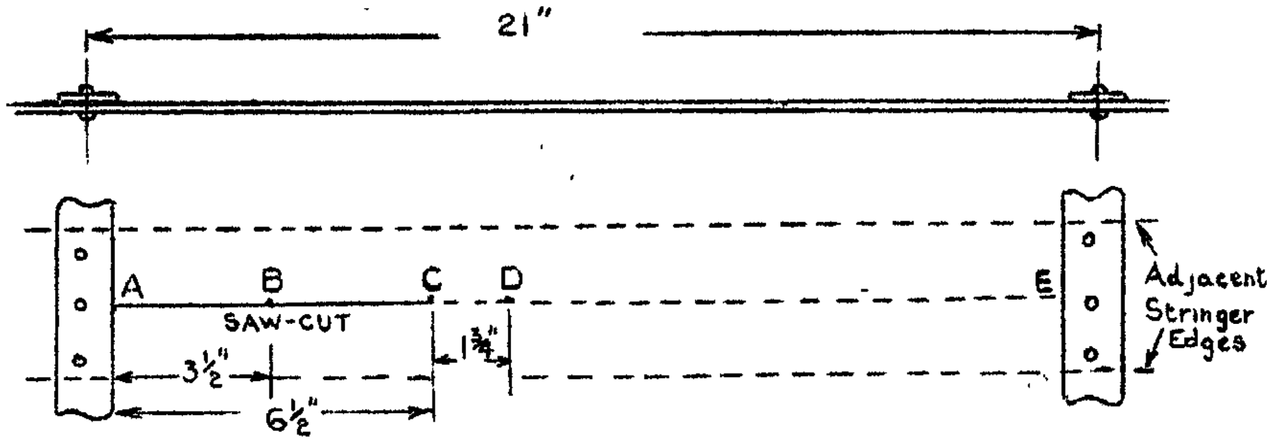

Fig.6

This test, like the 3rd test, simulates the case where, with hoops at 10.5 in. pitch, a hoop suddenly fails for some reason, thus throwing extra load on its two neighbours.

A pressure gauge used in this test showed that there was no drop in pressure during the last cycle when the crack ran across to the further hoop.

5 Remarks on the tests

For the recommended hoop pitch of about 10 in. it is clear from the 1st and 2nd tests that, even when a crack has reached a length of 5 in., it takes some 250 to 300 loading cycles to make it reach the adjacent hoops. It is there arrested so effectively that (according to the 2nd test) it fails to propagate under the hoops to the next bays even after 1400 cycles, i.e. some 4000 hours of flying life. The saw-cuts placed on the far side of the hoops after 250 cycles in Test No.1 show that, even after being artificially propagated to the next bays, the cracks show little disposition to spread, taking as they do another 1150 cycles to travel 1 inch.

The 3rd test is interesting as showing the degree of damage the skin-hoop combination can stand before finally giving way. Even after the crack had extended through hoop A right across from hoop B to hoop C the structure still had plenty in hand.

It is here worth estimating the nominal stress in these two hoops under such a condition. The qualifying adjective 'nominal' is used advisedly because it allows relative loads to be calculated on the simple basis of relative areas. The true stress in hoops B and C, when the intervening structure has ceased to take load, falls below the nominal stress by an amount depending on the redistribution of load caused by shear-lag.

On the basis of relative areas, therefore, we have, for each of the two hoops B and C, Original load in hoop $= npr\ell$

$$= \left(\frac{0.154}{0.154 + (10.5 \times 0.028)}\right) \times 8.25 \times 61.5 \times 10.5$$

$$= 1{,}800 \text{ lb} \qquad \text{(i)}$$

where
$$\left.\begin{aligned} n &= \text{ratio of material in hoop to that in skin-plus-hoop} = 0.34 \\ p &= \text{pressure} = 8.25 \text{ lb/in.}^2 \\ r &= \text{radius of cabin shell} = 61.5 \text{ in.} \\ \ell &= \text{pitch of hoops} = 10.5 \text{ in.} \end{aligned}\right\} \quad \text{(ii)}$$

Extra load in hoop due to continuous crack between hoops

$$= \frac{(pr \times 2\ell)}{2} = 5{,}300 \text{ lb.} \qquad \text{(iii)}$$

Adding loads (i) and (iii) and dividing by hoop area of 0.154 in.^{2}, we obtain a stress in each hoop of

$$= \frac{7{,}100}{0.154} = 46{,}000 \text{ lb/in.}^2 \qquad \text{(iv)}$$

which may be compared with the original stress deduced from (i) of $\frac{1800}{0.154}$

$$= 11{,}700 \text{ lb/in.}^2. \qquad \text{(v)}$$

Under the nominal stress given by (iv) the structure has still enough strength in hand to allow hoop B to be sawn half-way through, and therefore nominally have its stress doubled - from 46,000 to 92,000 lb/in.^{2}. The true stress, because of shear lag, must of course have been considerably less than this.

This whole test provides convincing proof of the toughness of this type of construction. Even after the middle hoop A had been artificially cut almost right through, it stood eight repetitions of load before giving up. It should also be noted that the consequent extension of the crack right across bay AC, sudden though it was, failed to make any impression on the barrier to its path.

In the condition thus brought about - one hoop and two bays of skin broken through - the structure could no doubt have stood many hundreds of load repetitions. This is indicated by the fact that one of the hoops had to be cut half way through before a static failure could be induced.

Tests 4 and 5 in which the pitch was increased to 16 in. - with a consequent increased skin hoop-stress and reduced support to the skin from the adjoining hoops - showed that under such conditions the crack will run after reaching a length of about 10 in. It was however effectively stopped by the hoops.

Like the 3rd test, but not so realistically, the 6th test simulates the case of a failed hoop (on the basis of a 10.5 inch pitch). The skin-hoop stress is now greater than even for the 16 in. pitch of Tests 3 and 4, and this accounts for its greater readiness to run, as evidenced by the critical length dropping from $10\frac{1}{2}$ in. to $8\frac{1}{4}$ in. In spite however of a 12 in. fast run, the crack had its further progress effectively barred by the hoop.

6 Efficiency of hoops in reducing skin hoop-tension

A cardinal merit claimed for the new method of construction is that <u>for the same working stresses</u> it entails little extra weight. In point of fact, a 'fail-safe' structure, for obvious reasons, justifies a substantially higher working stress than a structure based on a 'safe-life'. Without regard to this aspect of the matter, however, there is still very little weight penalty. Not because the weight of the hoops is negligible, but because the material devoted to the hoops is almost equally effective in reducing the maximum hoop-tension in the skin as the use of the same material in the form of added skin thickness. If the size and pitch of the hoops used in the first two tests described here were fitted from end to end of the Comet I cabin, the weight of the hoops alone would approach 500 lb, which, compared with something like 1,000 lb for the original 22 s.w.g. skin alone, is a very appreciable increase in weight. If, however, the extra 500 lb brings about a reduction in skin hoop stress comparable with that to be obtained by increasing the skin thickness itself by half - from the original 0.028 in. to 0.042 in. - the weight penalty will have been nil. It is of considerable interest therefore to quote the stresses actually measured by resistance strain gauges. The stresses were measured on the outer face of the original undamaged skin with the full pressure of 8.25 lb/in.^{2} applied, both before fitting the reinforcing hoops and after. The results are as follows:

Maximum skin hoop-stress before fitting bands (measured midway between a pair of standard former frames) = 13,500 lb/in.^{2}

Maximum skin hoop-stress after fitting bands (measured midway between bands) = 9,000 lb/in.^{2}

$$\text{Ratio} \qquad \frac{\text{skin stress with bands}}{\text{"} \quad \text{"} \quad \text{without} \quad \text{"}} = 0.68$$

which shows that the skin stress is reduced in very much the same ratio as

$$\frac{\text{weight without bands}}{\text{"} \quad \text{with} \quad \text{"}} = 0.66.$$

The weight in the bands has therefore practically paid for itself in the form of reduced maximum hoop-stress in the skin. That it is necessary not to exceed the recommended pitch of about 10 in., if the full effect of the bands in reducing the stress in the skin is to be achieved, follows from the observed fact that the maximum skin stress obtained with bands pitched 16 in. apart was 11,500 lb/in.^{2} - an increase of some 27% over the 9,000 lb/in.^{2} stress quoted above for the 10.5 in. pitch.

A further point worth noting is that, by limiting the pitch of the bands to 10 in. not only are the bands fully effective in reducing skin stress - the major objective of course - but the close pitch also discourages a crack from spreading in the intervening skin. For example, in the 2nd test (Fig.2) it took 100 load cycles to make the crack spread from C, where it was already 8 in. long to the edge E of the band. In the 6th test, however, (Fig.6) once the crack reached the point D, where it was 8 in. long, it shot across to the edge E in a single cycle.

7 Conclusions and summary

As mentioned in para.2, the allocation of material, as between skin and reinforcing bands, is at the choice of the designer. From the test results recorded here, it would appear that very satisfactory results can be obtained without putting more material in the bands than half that used for the skin - the actual cross-sectional areas per pitch length of skin and bands respectively were 0.295 and 0.154 in.^{2}. The guiding principle is that the structure should still have plenty of strength in hand after one band, together with the skin each side of it, has failed. That this principle is easily satisfied, with the material apportioned in the above manner, is proved by the results of the 3rd test above recorded.

How to reconcile this type of construction with the presence of windows is a problem that has been fully considered in Appendix II of ref.1 and need not therefore be discussed here.

The conclusions which the theory of refs.1 and 2 and the experimental results quoted here appear to justify may be listed as follows:-

(i) The suggested new method of construction makes the possibility of catastrophic failure of a pressure-cabin remote enough to be ruled out. Careful and frequent examination of the cabin shell for cracks becomes unnecessary, since they can be safely left until spotted in the course of ordinary maintenance inspection.

(ii) So long as the amount of material devoted to skin-plus-bands in the new construction is the same as that devoted to the skin alone in the conventional construction, the stress in the thinner skin of the former is little greater than the stress in the thicker skin of the latter. There is, therefore, no reason to expect cracks to begin appearing in the one before they do in the other. The difference is that in the one construction their occurrence can be contemplated with equanimity but not in the other.

It follows from this that, if the all-skin design is good enough to exclude the occurrence of cracks for 30,000 hours of flight, or whatever the 'safe life' is estimated at, the skin-plus-bands design should enjoy an equally long crack-free life. It should therefore be in first-class condition to carry on for another 30,000 hours or more when the conventionally constructed cabin has to be scrapped.

The likelihood of the new construction being able to outlast the conventional construction by anything up to five to one, or more, is a consequence of the fact that, in estimating the 'safe' life of an aircraft, the only solid basis is a tank test on a single specimen. The statistical scatter in fatigue tests of this type is such that the particular specimen under test, even if accepted as representing a cabin of no more than average quality, must still be assumed to have a life at least five times as long as the poorest specimen to the same specification. And since no production cabin can be credited with having a longer life than that deduced for the poorest specimen on test, the average cabin should have a life five times as long as the specified life.

(iii) The new construction will by-pass the necessity for expensive tank tests which, from being obligatory, will be undertaken only at the choice of the aircraft firm concerned, and with the purpose, not of specifying a 'safe' life, but of discovering any weak points, if any, in the design.

(iv) The above-mentioned advantages are to be obtained by the introduction of additional structural elements - the bands - that practically pay their way in the matter of weight. For, by limiting the pitch to 10 in., we make the material used in the bands nearly as effective in reducing the hoop stress in the skin as it would be if used as extra skin thickness.

(v) So far as design efficiency is concerned, what is stated under (iv) is only half the story. This is because, once the possibility of catastrophic failure is ruled out, a pressure cabin can be designed on structural principles alone, and not partly on the actuarial principles that must obtrude when structural strength is tied up with the conception of a 'safe' life.

8 Further developments

What has been said in items (i) to (v) suggests that, by adopting the proposed method of construction, a designer has a great deal to gain and very little to lose. Two points must however be mentioned as possible objections to the new method. One is the possible unsightliness of a series of bands. Such an objection would appear to need only to be mentioned to be dismissed. The bands, being only about 1.5 by 0.1 in., are very shallow and unobtrusive and their edges (necessarily abrupt in themselves to discourage the initiation of cracks) should be easily smoothed out by a suitable filling so as to be virtually invisible.

Fitting the bands to the outside of the cabin shell is, in the writer's opinion a most desirable objective. The thought of an outer skin held down by stiffish bands through the medium of rivets in tension is, or should be, to every designer an abhorent thought. The only valid objection is that outside bands may have an unwelcome effect on the overall drag of the cabin.

Theory does not give a decisive answer on this point and it has therefore been decided to put the matter to a direct test. The experiment is straightforward, for it needs only to test a fast aircraft with and without bands and to note any significant change in speed. The bands can be of any convenient material and need not be positively fastened. The result of such a test will form the subject of a further note in the near future.

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