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“The Failure of Short Tubular Struts of High-Tensile Steel.”

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INTRODUCTORY.

THE phenomenal progress which has been made in the development of aeroplanes during the last six or seven years, especially since the beginning of the war, has made it necessary for engineers to pay attention to the strength of many new materials and forms which have come into use. One of the most important of these new structural forms is the tubular strut used in aeroplane frames. They may perhaps be defined more suitably as old forms applied to a new purpose, in which it is extremely important that the maximum of strength shall accompany the minimum of weight.

The introduction into general use of nickel, chromium, and nickel-chromium steels in place of carbon steels has enabled aeroplane manufacturers still further to reduce the weight of their frames without loss of strength. These tubular struts when under load may fail as long pillars by general flexure, or the failure may take the local form of collapse called crinkling, generally close to the ends. In either case of failure, the walls of the tube become corrugated; and, in the case of short tubes, if the loading be continued a series of folds or crinkles will form. This local flexure is more likely to occur in thin than in thick tubes; and as the use of high-tensile steel tends towards thinness, experimental work on these is of special importance. It was with a view to adding to such knowledge as already exists, especially as regards high-tensile steel, that the Authors undertook the work described in the present Paper, at the suggestion of the Royal Aircraft Factory, who supplied the material used in the experiments. The term “elastic breakdown” used in this Paper means the stress at which the relation between stress and strain departs from the linear law. The

expression "crinkling stress" is used for "elastic breakdown" in the cases where this latter is below the elastic limit of the material. The most recent important information available on the subject of crinkling is a Paper¹ by Mr. R. V. Southwell, which gives also a fairly complete bibliography of other previous work in connection with the subject.

THE SPECIMENS TESTED.

The sizes of the tubes used in the experiments are given below; they were limited by the power of the machine (30 tons) which it was intended to use, and are divided into the two classes "Annealed" and "Hard" or "Unannealed."

	Diameter (inches).	Gauge.
Annealed	$\frac{3}{4}$	22, 18
	1	20, 18, 16
	$1\frac{1}{4}$	22, 20, 18, 16, 14, 12
	$1\frac{1}{2}$	24, 20, 18
	$1\frac{3}{4}$	20, 12
	2	20
Hard (Unannealed). .	$\frac{3}{4}$	22
	1	20, 18
	$1\frac{1}{4}$	20, 18, 12
	$1\frac{1}{2}$	24, 20, 18
	$1\frac{3}{4}$	12

Not less than three samples of each size were prepared by cutting of lengths each equal to from two to three diameters, after which their ends were carefully machined and in many cases ground so as to be truly perpendicular to the axis.

CHEMICAL COMPOSITION.

The tube material was a nickel-chromium steel; its principal constituents were:—

Carbon	0·2 to 0·3 per cent.
Nickel	4 to 5 per cent.
Chromium	1 to 1·5 per cent.

TENSILE STRENGTH.

Tensile tests were carried out on some of the tubes, and the results are given in the following Table:—

¹ Phil. Trans. Royal Soc., 1914.

TABLE I.—TENSILE STRENGTH OF THE TUBE MATERIAL.

	Mean thickness.	Mean outside diameter.	Yield point.	Maximum Stress.	Elongation per cent. on 2 inches on 8 inches.		Elasticity
			Tons per Sq. In. 37	Tons per Sq. In. 46			Lbs. per Sq. In. 28.6×10^6
Annealed . . .	0.029	0.75			19	11.5	
	0.038	0.999	38.5	47.2	23	14	30.4×10^6
	0.076	0.998	36.4	41.3	28	14.4	29.9×10^6
	0.101	1.246	38.1	49	28.5	17	28.4×10^6
Hard . . .	0.034	1.248	..	104.5	5.1	4	27.8×10^6
	0.048	0.999	..	99.2	7	5.4	27.9×10^6
	0.097	1.238	..	75.1	14	6	26.3×10^6

The yield point for the material of the hard tube practically coincided with the maximum stress.

THE APPARATUS USED.

It was desired to obtain autographic records of the load and of the shortening it produced; and the first problem was to adapt the machine available for this work so as to produce the records with sufficient accuracy. The machine used was a 30-ton Amsler-Laffon oil-pressure machine, which works on the hydrostatic principle. A head of mercury transmits pressure through a differential piston to an oil-chamber in communication with a vertical cylinder, into which an accurately fitting ram can slide. This pressure, acting upon the ram, was transmitted to the specimen placed upon it. It was thought that variations in the thickness of the oil film surrounding the ram might possibly to some extent vitiate the results, but extensometer readings taken on a solid specimen placed at a number of different points on the end of the ram, showed that for the same loads the readings were sensibly constant for much larger changes in position than were likely to occur. The mercury column to which the load was eventually due was contained in a celluloid tube, and on the top of this column was supported a plunger or float, whose height was proportional to the load on the specimen. The motion of this plunger was utilized to record the height of the column, and hence the load on the specimen. An oscillatory motion was given by a small motor to the differential piston about its axis, which besides enabling it quickly to take up any new position of equilibrium by eliminating friction

in an axial direction, at the same time set the mercury vibrating and caused the top of the column along with the plunger and the load-recording mechanism to oscillate through a small distance and thus ensured smooth working. The shortening of the specimen under the load was in reality the diminution of the distance between the platens of the machine; this movement was magnified by a scissors device, from which it was communicated to the recording drum by means of a fine wire.

METHOD OF HOLDING THE SPECIMENS.

In order to avoid bending of the specimens due to variation in the thickness of the different parts of their sides and to the load

line being not truly axial, it was decided to transmit the load through a pair of hardened and ground steel parallel plates. Friction between the plates and the specimen invariably caused the crinkles to form at or near the ends, and an attempt was made to strengthen the ends either by plugging them or by sinking them into sockets, or both. The four methods of holding the ends are shown in *Figs. 1* (P, Q, R, S).

In spite of all the precautions taken, crinkles did form at or near the ends, and for this reason extensometer readings were in some cases taken at the same time as the autographic record was being formed. For this purpose a Martens extensometer was used, and as it measured the shortening of opposite sides it was possible to find out whether any bending was taking place.

THE RESULTS OBTAINED.

The results obtained during these experiments are included in the following:—

Autographic records, of which one was taken for each tube.

Stress-strain curves from extensometer-readings.

Notes taken during crinkling.

Photographs of the tubes after crinkling had taken place.

The Autographic Records.—These were taken in the case of all tubes tested, and prints from typical records are shown in *Figs. 2 to 5*. The letter A on each record marks the point where the crinkles begin to be noticeable by micrometer measurement. The letter C marks the termination of the experiment; here the machine was reversed and the load allowed to fall to zero. The irregularities on record 5, indicated by the letter B, correspond to the formation of cracks in the specimen. The elastic breakdown is found from these records by noting the point at which the line ceases to be straight, at the end of the elastic condition. It was not as a rule considered necessary to continue the records beyond the formation of the first crinkle, but in some cases two or three crinkles were formed. *Fig. 2* corresponds to the formation of three crinkles. It will be seen from this figure, and it was found always to be the case, that where more than one crinkle was formed the maximum load reached during the formation of the first was greater than that reached during the formation of subsequent ones.

The Records for the Annealed Tubes.—Three distinct types of record were obtained, showing a consecutive and gradual development the one from the other. Those corresponding to values of t/r greater than 0.1 showed a decided yield, and resembled the earlier portion of stress-strain curves from tensile tests of the tubes. *Figs. 2 and 3* are typical of these. Where the value of t/r was slightly less than 0.1, the yield is not clearly defined and the curves are of the form shown in *Fig. 4*. For values of t/r about 0.05 and less, the records are very similar to those for the hard tubes. The changes in the shapes of the records that take place about the value $t/r = 0.1$ indicate that there is here a critical region, and that for values of t/r less than 0.1 a different set of phenomena is involved as compared with greater values.

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Autographic Records: Hard Tubes.—The records for the hard tubes are approximately of one type, which is exemplified in *Fig. 5*. The tensile tests (Table I) carried out on the hard tubes showed that the yield point approached or coincided with the maximum

Fig. 3.

stress. The shape of the initial part of the record for the thick tube (*Fig. 5*) is practically the same as the stress-strain curve from a tensile test of the tube. It will be noticed from the records that

Fig. 4.

for both hard and annealed tubes the load falls off more rapidly from the maximum as t/r diminishes.

General Plotting.—This shows at a glance the results obtained from all the tubes tested. There are two sets, those for the annealed tubes and those for the hard tubes (*Fig. 6*). In each case the

value of t/r for the particular tube is taken and plotted against the stress at elastic breakdown. By drawing mean lines through the plotted points, it is seen that the two pairs of lines are obtained,

Fig. 5.

and it will further be noticed that in each pair a crossing takes place at a point not very far from $t/r = 0.1$. There thus appears

Fig. 6.

to be a critical region about a value of $t/r = 0.1$. As pointed out earlier in the Paper, the existence of this is borne out, especially in the case of the annealed tubes, by the difference in the shapes of

the records corresponding to values of t/r less than 0.1 as compared with those corresponding to values greater. The theoretical investigation of Lilley and Southwell showed that for ideal tubes the critical value of t/r should be about 0.0038.

Consideration of the pair of lines for the annealed tubes (*Fig. 6*) shows that there is a definite crinkling stress up to $t/r = 0.1$, and that when t/r exceeds this the elastic breakdown corresponds to the elastic limit of the tube material.

The general nature of this last-mentioned result was, the Authors believe, first pointed out for mild steel by Mr. W. H. Barling. In confirming them, the Authors fully realise that with perfectly true and symmetrical tubes, and with loading conditions approaching mathematical accuracy, there might be no discontinuity in the line—probably would not be. But from the practical view of the designer this critical region of t/r does appear to exist. From *Fig. 6* it is found that for the annealed tubes the crinkling stress in tons per square inch is approximately given by—

$$f_c = K \cdot \frac{t}{r}$$

where $K =$ about 300 and t/r is less than 0.1.

The results for the hard tubes were complicated by the fact that the thicker ones appeared to be softer than the thinner ones, as is indicated by the results of the tensile tests (see Table I). To test this further, a thick tube ($t/r = 0.172$) was machined down inside and outside until $t/r = .055$, and tested. The result is shown in *Fig. 6* by two concentric circles, and serves further to indicate that this thick tube was softer than the thinner ones. It appears probable that if the "hard" tubes had been of the same degree of hardness throughout the pair of lines for the hard tubes may have been similarly situated to those for the annealed ones. The values of the elastic breakdown as plotted in *Fig. 6* were all taken from the records. There is a possibility of error of about 2 tons per square inch for the lower points on the curve for the annealed tubes, and up to about 5 tons per square inch for the highest points on the curve for the hard tubes. What effect such a possible discrepancy may have can be seen by an examination of the figure.

It was found when records were taken for different end conditions (*Fig. 1*), that the variations in the values of the elastic breakdown lay within the above possible error; an examination of Table II of general results will indicate these variations.

PLOTTINGS FROM EXTENSOMETER READINGS.

In the four curves plotted on *Fig. 7* from the extensometer readings, it is to be noted that in each pair the individual curve corresponds to readings taken on opposite sides of the specimen, and that the parallelism of those pairs of lines indicates that there

Fig. 7.

is very little bending taking place; also the elastic breakdown stress is sensibly the same as that given by the records. Extensometer readings were taken in only about fifteen cases, but in each case the value of the elastic breakdown stress indicated was sensibly the same as that given in the corresponding record. In some cases where the ends of the tubes were plugged (types R and S, *Fig. 1*),

incipient crinkles formed along a considerable length of the tube before the final crinkling occurred; this invariably took place near the limits of one of the plugging disks.

NOTES TAKEN DURING CRINKLING.

It was considered advisable to note the several stages of the deformation as the tube crinkled, and short notes were drawn up for each experiment. Summarizing briefly, the following may be given as among the chief points:—

As the crinkles formed, their shapes in plan were either circular, oval, or approximately triangular. For values of t/r greater than 0.1 the crinkles were practically circular. For values about 0.1 and slightly less, the shapes are decidedly oval. There were thus two points of maximum curvature—opposite to each other—around the perimeter of the crinkle. For values of t/r about 0.05, three points of maximum curvature developed; these were situated approximately equidistantly around the perimeter. The same state of affairs was noted for the hard tubes, but here cracks generally formed at the points of maximum curvature. The position of the points of maximum curvature appeared to be determined by the geometrical shape of the tube; for instance, one of these generally situated near the thinnest side.

Types of symmetrical deformation of crinkling similar to the above are discussed in a note by Mr. A. Mallock (Proc. R.S., 1908).

Mr. Southwell found that the critical load for an ideal tube for the “lobed” type of deformation was $\frac{k^2 - 1}{k^2 + 1}$ times that for the circular type, where k has the values 2, 3, etc., corresponding to the number of lobes. $k = 2$ evidently corresponds to the oval shape of crinkle, and $k = 3$ to the triangular shape. The critical load for an ideal tube, as given by the formula for the lobed type of deformation, is thus less than for the circular type; and it is significant that this type corresponds to the region of t/r less than 0.1. The wave-lengths were measured, approximately, directly from the specimens, and it was found that these were from 30 to 100 per cent. longer than those given by the theoretical formulas of Messrs. Southwell and Lilley. Those approaching more nearly to the theoretical lengths were for the thinner tubes, and hence corresponded to the region of t/r less than 0.1.

CONCLUSIONS.

The Authors consider the following conclusions to be justified by the results of the above experiments:—

(1) In the case of the annealed tubes, there is a definite crinkling stress which varies, approximately, with t/r so long as this does not exceed 0.1.

(2) For values of t/r greater than 0.1 the elastic breakdown is identical with the elastic limit of the material.

(3) The results appear to confirm the theoretical conclusions of Mr. W. H. Barling and his experimental results for mild steel tubes.

(4) For tubular struts of the hard material here tested, special attention is necessary when t/r is greater than 0.1, whereas in annealed tubes this caution is needful where t/r is less than 0.1.

(5) The wave-lengths as measured on the specimens are from 30 to 100 per cent. longer than those given by the theoretical formulas of Southwell and Lilley.

(6) The difference in the crinkling stress between a tube of exact geometrical form and an actual tube is due chiefly to a slight deviation from this form in the first instance, and for an appreciable increase in the deviation greater than this, the crinkling stress will be sensibly constant.

The Authors desire to thank the Governing Body of the Manchester School of Technology for the opportunities afforded for the carrying out of these experiments; also Mr. W. H. Barling and Mr. H. H. Webb for the facilities afforded, and for much valuable advice; and Professor Field for the keen interest he has throughout taken in the experiments, and the helpful counsel he has given.

This Paper is accompanied by 3 photographic prints and 10 cloth tracings, from which the Figures in the text have been selected.

NOTE AS TO GENERAL RESULTS.

On the diagrams showing autographic records, *Figs. 2 to 5*, are given brief notes of the main results for the particular tubes in question. These figures are incomplete, because they apply only to a comparatively few tubes; the data are amplified in the more complete Table II, which is given on pp. 392-393.

TABLE II.—ANNEALED TUBES.

No. of Experiment.	Thickness (mean of four measurements).	Outside diameter (mean of four measurements).	Length.	Thickness mean rad. <i>t/r</i> .	Elastic breakdown. Tons per Sq. In. (record).	Conditions of ends. (See Fig. 1.)
	Inches.	Inches.	Inches.			
21	0.025	1.502	3.760	0.0339	18.1	R
22	0.0285	0.752	1.912	0.0789	26.1	P
23	0.034	1.498	3.777	0.0465	12.8	P
24	0.034	1.497	3.972	0.0465	12.2	P
25	0.034	1.497	4.229	0.0465	11.8	S
26	0.034	1.248	3.027	0.0561	17.4	P
27	0.034	1.248	3.480	0.0561	16.1	P
28	0.038	0.999	2.517	0.0791	27.4	P
29	0.038	0.997	2.980	0.0792	27.4	Q
30	0.038	0.998	2.455	0.0791	27.9	R
31	0.040	1.771	4.440	0.0463	14.4	P
32	0.040	1.771	4.444	0.0463	14.4	P
33	0.040	1.771	4.469	0.0463	17.5	R
34	0.043	2.170	5.462	0.0403	16.8	P
35	0.043	2.171	5.840	0.0403	15.7	P
36	0.043	2.172	5.986	0.0403	15.1	S
37	0.0495	1.503	3.773	0.0681	19.8	P
38	0.0495	1.503	3.597	0.0681	20.2	R
39	0.048	1.249	3.125	0.080	23.6	P
40	0.048	1.250	3.635	0.080	24.1	Q
41	0.048	1.250	3.010	0.080	23.6	R
42	0.0485	1.252	3.621	0.0805	24.1	P
43	0.049	0.999	2.508	0.103	30	P
44	0.048	0.999	2.761	0.101	28.4	P
45	0.049	0.999	2.743	0.103	28.4	R
46	0.065	1.252	3.257	0.109	30.1	P
47	0.0645	1.252	3.237	0.109	30.2	P
48	0.076	1.000	2.514	0.164	31.5	P
49	0.076	0.999	3.020	0.165	29.3	Q
50	0.076	0.999	2.775	0.165	29.3	R
51	0.101	1.246	3.522	0.177	31.6	P
52	0.102	1.246	3.507	0.178	29.4	S
53	0.1065	1.252	3.580	0.186	27.1	P

TABLE II—continued. HARD TUBES.

No. of Experiment.	Thickness (mean of four measurements).	Outside diameter (mean of four measurements).	Length.	Thickness mean rad. t/r.	Elastic breakdown. Tons per Sq. in. (record).	Conditions of ends. (See Fig. 1.)
	Inches.	Inches.	Inches.			
61	0.0315	0.752	2.220	0.0875	45.3	P
62	0.0315	0.750	1.760	0.0880	49	R
63	0.034	1.247	3.254	0.0561	50.8	P
64	0.034	1.244	3.246	0.0561	46.8	P
65	0.036	1.503	3.796	0.0491	52.1	P
66	0.036	1.501	3.978	0.0491	50.0	P
67	0.036	1.500	4.246	0.0491	48.0	R
68	0.0365	1.500	3.762	0.0498	45.5	P
69	0.044	1.502	3.809	0.0603	49.2	P
70	0.045	1.501	4.214	0.0619	51.2	P
71	0.0465	1.500	2.958	0.064	48.4	R
72	0.049	1.254	3.123	0.0813	53.3	P
73	0.049	1.254	3.625	0.0813	53.3	P
74	0.048	1.254	3.008	0.0798	53.4	R
75	0.049	0.999	2.506	0.103	51	P
76	0.049	0.998	3.000	0.103	47.5	Q
77	0.048	0.999	2.522	0.101	52	S
78	0.098	1.239	3.125	0.172	38.6	P
79	0.096	1.240	3.517	0.172	39.6	P
80	0.095	1.239	3.502	0.174	34.9	R
81	0.104	1.756	3.754	0.126	41.4	P