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INCREASE OF THE SPECIFIC LOAD UNDER TENSION, COMPRESSION, AND BUCKLING OF WELDED STEEL TUBES IN AIRPLANE CONSTRUCTION BY SUITABLE TREATMENT OF STRUCTURAL STEEL AND BY PROPER DESIGN

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INCREASE OF THE SPECIFIC LOAD UNDER TENSION, COMPRESSION, AND BUCKLING OF WELDED STEEL TUBES IN AIRPLANE CONSTRUCTION BY SUITABLE TREATMENT OF STRUCTURAL STEEL AND BY PROPER DESIGN*

By J. Müller

Although recently the light-metal stressed-skin construction has largely replaced the welded-steel-tube framework construction for airplane structures, it will nevertheless not be possible entirely to dispense with the steel tube as a tension and compression element. In the landing gear, engine mounting and also as surface supporting strut the steel tube, on account of the simplicity of the welded joints it permits and its outstanding strength characteristics for airplanes of all types, will continue as before to maintain its place.

In this report some considerations and test results are presented that may lead to higher tension, compression, and buckling stresses than is possible with the welded-steel-tube struts of the usual familiar construction. The new construction method indicated, which makes possible a considerably better material utilization and hence a saving in weight, has been tested in a number of Focke-Wulf types also in series production and has fully justified itself.

In any structural design problem, the lengths of the struts and the loads to be taken by them are generally given. An airplane framework structure must, on account of the various flight and landing conditions encountered, often be able to take up a certain tensile and also a definite pressure loading. Often, too, only one type of loading occurs.

As is known, the properties of the material that determine the cross-sectional area and hence the weight of the

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*"Erhöhung der spezifischen Belastbarkeit bei Zug, Druck und Knickung von eingeschweissten Stahlrohr-Fachwerkstreben im Flugzeugbau durch Massnahmen werkstofftechnischer und konstruktiver Art." Luftfahrtforschung, vol. 16, no. 1, Jan. 10, 1939, pp. 14-17.

tube welded at each end are: in the case of tensile load, the strength and the elastic limit of the material in the region annealed by the weld; in the case of compressive load, assuming sufficiently high slenderness ratio of the strut, the elasticity modulus corresponding to the buckling relation of Euler, this modulus being independent of the condition of the material whether welded or unwelded; in the case of lower slenderness ratio, the stretching or buckling limit of the welded tube.

It may be seen that with the exception of the case where only buckling stress in the Euler region occurs, the zone affected by the weld is always of decided significance for the dimensions and weight of the strut. The manner in which the steel tubes applied in airplane construction are affected as regards metallography and strength by the weld is known (references 1 and 2). An essential point brought out is that the tensile and compressive strength of butt-welded tubes corresponds to the strength of the unwelded, annealed tube, so that it assumes a minimum value which is characteristic of each type of steel. Cold or hot joining of the strut to be welded therefore, also outside the Euler range, is of no significance and the heat treatment of a tube cannot be utilized either for tensile or compressive stress unless the welded framework is treated as a whole, which treatment, however, on account of the size and deformation feared in hardening is generally impossible.

There was no disadvantage in this as long as for airplane construction only unalloyed steel tube was employed whose strength properties cannot be essentially increased over those of the welded state. This was also the result reached by A. Rechtlich in his comprehensive investigations of 1930 (reference 1, p. 410), namely: "that the weld up to the very small slenderness ratios is without effect also in the non-elastic range." The buckling values of welded unalloyed tubes for slenderness ratios greater than 15 lie as high as for those of the unwelded tubes.

The main results of the compression and buckling tests of Rechtlich with two kinds of tube of various carbon content (0.1 to 0.15 percent and 0.3 to 0.5 percent) are shown in figure 8.

Since the introduction of chrome-molybdenum steel tubing in the Albatros works at Berlin-Johannisthal, the object at Albatros and later at Focke-Wulf was consistently followed of utilizing the heat treatment possibilities of

this steel as far as possible also for welded-tube struts. The essential results of the compression and buckling tests will be reported in what follows. The buckling ($\lambda > 10$) was carried out on a testing machine between knife edges, so that the degree of end fixing was practically equal to zero. Each individual strut after the deformations, which for the loading in the elastic range were observed with gages connected at the sides, was centered by a displacement arrangement mounted at the knife edges. The specimens for the compression tests ($\lambda < 10$) were compressed between two flat plates with a sphere segment connected between, in order to obtain as even pressure distribution as possible. The tubes were straightened before the buckling and the ends ground even.

The test specimens were of American, Swedish, and German origin. (See table I.) In all cases, however, only chrome-molybdenum steels were used which correspond in composition to the aviation material 1452. In the state in which they were supplied the tubes were heat-treated as is customary and apparently only after the last cold-drawing. The minimum strength of the steel 1452 used as a basis for the computation is in the annealed and welded state 60 kg/mm². In the heat-treated state a value of 120 kg/mm² may be obtained.

Figure 1 shows the results from three buckling tests of the year 1930 with chrome-molybdenum steel tubes which were cut from the corresponding rods in the delivery state and were thus buckled unchanged. Corresponding to the increase in the yield point under compression and the tensile strength, there is found an improvement in the buckling strength as compared with the unalloyed steel tubes. (See table I.)

Figure 2 gives the results of a series of tests of 1931. They were specially carried out because the two pairs of buckling values of tubes 35 x 1 and 40 x 1 were so different, being in the reverse sense to what was expected from their slenderness ratios, that a more accurate investigation of the tubes was justified. The values obtained are given in table II and the grain structure shown in figures 3 and 4.

The grain structure pictures show immediately the different strength properties. In the second case, the harder component (iron carbide) is far more uniformly distributed than in the 35 x 1 tube. This leads to the considerably higher tensile limits of this tube and these again to the

higher buckling strength in the plastic region. The grain structure and properties of the 40 × 1 tube may be attained with the steel 1452 by heat treatment.

In 1932 a series of buckling rods of average slenderness ratio 35 to 60 were improved to a strength of about 110 kg/mm². The buckling-strength curve obtained rises along the Euler curve up to about 60 kg/mm² and in the Tetmajer region still higher as shown in figure 5 (numerical values given in table 3). As a result of more pressing problems, this work was not ended until 1934 with the following two larger series of tests:

First there was determined the effect of an annealed weld at the end of the heat-treated buckling rod, since it was supposed that such an effect on the buckling curve would be relatively small. Eighteen rods of the slenderness ratio under consideration were first improved by heat treatment from 110 to 125 kg/mm². Then at both ends 10 millimeters distant from the latter a butt joint was made by welding a saw cut that did not quite go through.

Figure 6 and table IV show that in the entire region lying below the Euler curve, that is, up to the slenderness ratio 55 a minimum buckling stress of 60 kg/mm² may with certainty be attained. It is to be noted that also for this high slenderness ratio buckling failure occurred at the ends while the rod itself remained unchanged over its entire length. Compression pieces of the length of their diameter which pieces were treated and welded in the center gave the same compressive strengths (fig. 6). Those values for which failure could not be attained with the test machines available are indicated with an arrow pointing upward.

Considerably higher buckling stresses below the Euler curve may be attained if care is taken to see that the above-mentioned buckling failures are avoided, i.e.: if the struts before the treatment are so designed that in the regions which are again annealed by welding to the framework the thickness of the walls is made correspondingly greater than in the remaining region not affected by the heat of the weld*. The reenforcing of the ends is most economically

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*This process is legally protected by the firm of Focke-Wulf Flugzeugbau G.m.b.H., Bremen, through DRP. Inventor: Dr.-Ing. Müller, Bremen.

effected as seen in figure 7 by the welding of thicker tube ends with heat-treatable welding wire 1453.

Thirty-three specimens according to figure 7 with a heat-treated (110 to 120 kg/mm²) and an untreated weld at each end and with slenderness ratios of 20 to 55 were thus prepared and buckled between knife edges. The buckling stresses attained are shown in figure 8 and it may be seen by comparing with the other limiting curves that the gain is considerable.

This is particularly the case for slenderness ratios of 20 to 60. It is only at slenderness ratios higher than 75 that the strain limit of the annealed chrome-molybdenum steel tube is sufficient to attain the Euler curve with the buckling stress. Above this slenderness ratio, an increase in the buckling load by heat treatment is entirely impossible. The strong struts that particularly affect the overall weight of the airplane lie, however, within the range of moderate slenderness ratios where the fact is also to be taken into account that the effective slenderness ratio becomes smaller through connection in the framework.

In the case where the tensile strength is the factor of importance for the dimensioning of a welded steel tube, it is possible by the design method described to save weight in each case, i.e., independent of the length. In the normal design with constant cross section only the annealing strength of the steel can be considered, independent of the strength before welding. If the ends, however, were reenforced before welding and the rod then treated, each section can be dimensioned to correspond to its strength. The gain in weight thus attained approaches, with increasing length of strut, the ratio of annealing strength to heat, treating strength of the steel, i.e., for 1452 half the weight of the strut.

Figure 9 shows a section of the landing gear of the Fw 200 "Condor" in which reenforced heat-treated struts were applied.

Translation by S. Reiss,
National Advisory Committee
for Aeronautics.

1. Rechtlich, A.: Grundlagen für die konstruktive Anwendung und Ausführung von Stahlrohrschweissungen im Flugzeugbau. Jahrbuch 1931 der Deutschen Versuchsanstalt für Luftfhart, pp. 379-438.

2. Müller, J.: Untersuchung über die Schwingungsfestigkeit der Schweissverbindung von Stahlrohren verschiedener Zusammensetzung, die für Konstruktionszwecke, insbesondere für Fachwerkbau, in Betracht kommen. Diss. 1932 Berlin.

TABLE I (fig. 1)

Buckling and Resistance Coefficients of

Non-Heat-Treated Chrome-Molybdenum Steel Tubes

Origin	λ	σ_K kg/mm²	D x S mm	$\sigma_{0.02}$	$\sigma_{0.2}$ kg/mm²	σ_B
American	81.5	30.5	25.5 x 1.5	47.5	71	81
	60.9	42.4				
	40.6	52.9				
	40.6	48.7				
	25.2	61.3				
	24.9	53.2				
	81.8	26.4	25.5 x 3	45.8	60	82
	61.4	38.4				
German	25	50.0	30 x 1	40.5	54.5	66.4
	25	50.5				
	60	46.4				
	40	49.6				
	40	49.3				
	80	31.7				
	80	31.8				
	60	41.4				
Swedish	29.5	56.6	30 x 1	39	53.5	62.7
	60	48.3				
	80	34.5				

TABLE II (fig. 2)

Buckling Coefficients and Other Properties of Chrome-Molybdenum Steel Tubes in Delivery State

D x S mm	λ	σ_K kg/mm²	$\sigma_{0.02}$ kg/mm²	$\sigma_{0.2}$ kg/mm²	σ_B kg/mm²	Structure
35 x 1	30	45.6	33.5	50	62	Granular pearlite in free ferrite (fig. 3)
35 x 1	30	45.7	37	51	64	
40 x 1	47	56.9	50	68	85	Sorbite without free ferrite (fig. 4)
40 x 1	47	59.7	-	72	83	
32 x 1	62	40.7	-			-
32 x 1	62	43.6				
34 x 0.75	68	42				
34 x 0.75	68	42				
36 x 0.75	47	45				

TABLE III (fig. 5)

Buckling and Tensile Strength of Heat-Treated Chrome-Molybdenum Steel Tubes

D x S mm	σ_B kg/mm²	λ	σ_K kg/mm²
14 x 1	108.7	53.5	60
		60	54.5
26 x 1	112.3	36.5	75
		43.5	70.5
		37	66.5
		48.5	64.5
		55	56.5
		60	50.5

TABLE IV (fig. 6)

Buckling Tests on Heat-Treated and Then Welded

Chrome-Molybdenum Steel Tubes

D x S mm	σ_B kg/mm²	λ	σ_K kg/mm²
30 x 1	118.4	40	70.6
	119.1	40	69.3
	113.5	27.2	68.3
	114	27.2	70.3
35 x 1	124.5	50	> 71.2 failure not obtained with given testing machine
	120.2	50	
	124	46.5	
	125.8	46.5	
	121	40	
	126.5	29.1	
40 x 0.75	112.2	50	63.3
	114	50	63.8
	127	46	68.3
	-	30	63.8
40 x 1	111	50	> 65.5
	-	50	> 64.7
	127	48.5	> 65.5
	119	48.5	> 63.5

TABLE V (fig. 8)

Buckling Tests on Heat-Treated Chrome-Molybdenum

Steel Tubes with Reenforced Ends

D x S mm	σ_B kg/mm²	λ	σ_K kg/mm²
28 x 1	117.5	55	69.7
	117	50.3	77.4
	111	50	76.8
	120.2	50	71.5
	117	50	70.5
	108.5	50	70.6
	117.5	47.5	86.8
	118.9	47.5	85.7
	121	45	86.5
	109.3	44.8	86.5
	113.2	44.8	93.5
	121.5	40.3	91
	123	40.2	88.7
	121.9	34.8	93.1
	121	30.2	> 91
	113	30	> 91.5
	-	20.4	> 91
	-	20.3	> 91.5
36 x 0.75	111	55	72
	109.5	55	64.8
	113.5	50	76.8
	104	49.8	78
	108.5	46.7	83
	125.1	45.5	90.8
	116	45	> 94.3
	111.4	45	80.8
	114.5	40	92.2
	111	39.7	89
	116.5	39.7	90.2
	113.4	29.9	> 96.5
	116.5	29.9	92.7
	113.4	19.6	> 96.3
	117.2	20	>100.1

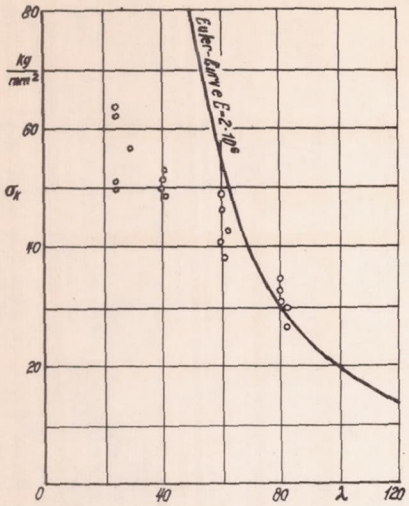

Figure 1.- Buckling tests with unheat-treated chrome-molybdenum steel tubes.

Figure 3.- Grain structure of 35x1 steel tube: granular pearlite with free ferrite. Magnification 500 times.

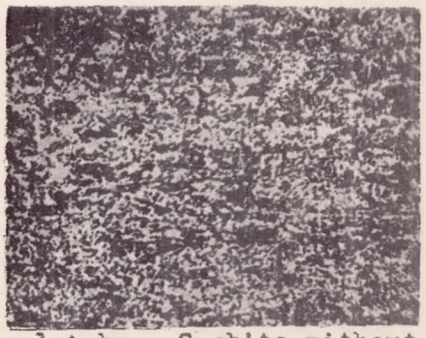

Figure 4.- Grain structure of 40x1 steel tube : Sorbite without free ferrite. Magnification 500 times.

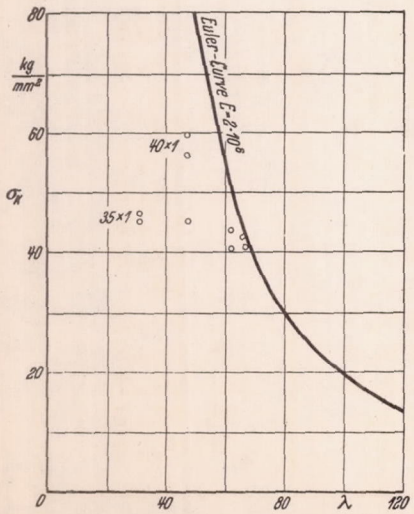

Figure 2.- Buckling tests with chrome-molybdenum steel tubes in the delivered state.

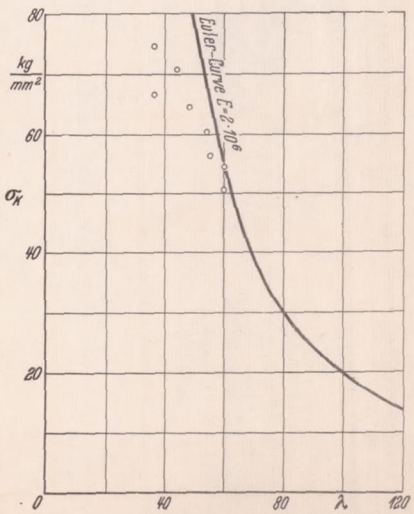

Figure 5.- Buckling tests with heat-treated chrome-molybdenum steel tubes.

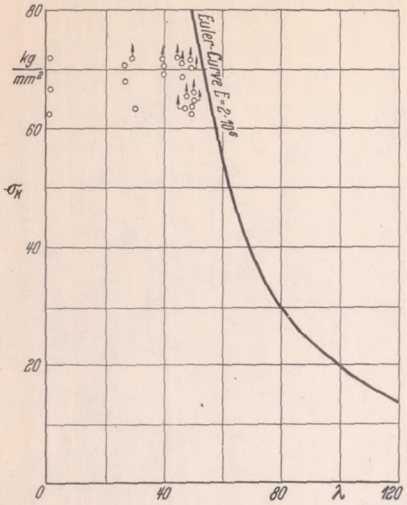

Figure 6.- Buckling tests and compression tests with heat-treated and then butt-welded chrome-molybdenum steel tubes.

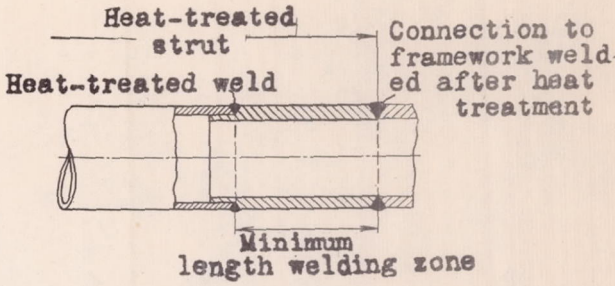

Figure 7.- Reenforced end of heat-treated framework strut to be welded

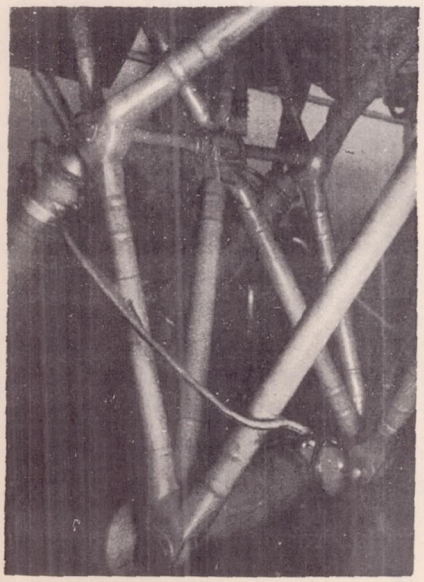

Figure 9.- Section of landing gear of Fw200 "Condor" with welded heat-treated framework struts.

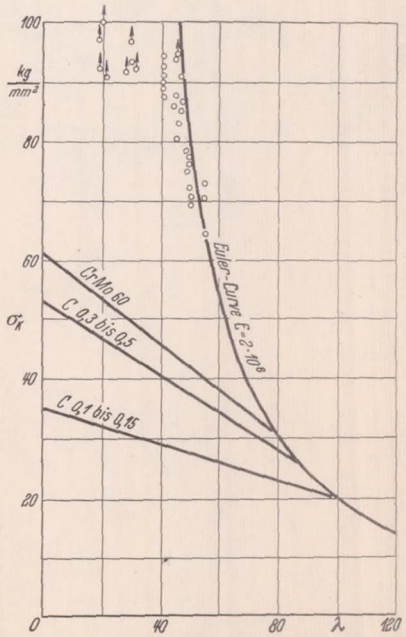

Figure 8.- Buckling tests with heat-treated chrome-molybdenum steel tubes with reenforced ends (the two lower limiting curves after Rechtlich).