TECHNICAL NOTES

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

No. 560

A COMPARISON OF CORROSION-RESISTANT STEEL

(18 PERCENT CHROMIUM - 8 PERCENT NICKEL)

AND ALUMINUM ALLOY (24ST)

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In the selection of materials for aircraft applica-
tion, it is not enough to make the selection on a strength-
weight basis alone. A strength-weight comparison is sig-
nificant but other factors must be considered, for while a
material with a high ratio of strength to weight may be
perfectly satisfactory for one use, it may be totally un-
fitted for another. It is essential, among other things,
that the probable nature, magnitude, and direction of the
principal stresses be given special consideration.

The following analysis has therefore been made with
this in mind. An attempt has been made to cover insofar
as possible the major, but not all of the points, that a
designer would consider in the use of "18-8", as it is
commonly referred to, and 24ST aluminum alloy, as applied
to aircraft. 24ST was selected for this comparison as it
has practically replaced 17ST for aircraft construction
and it appears to have the best combination of properties
of the alloys now available for this purpose. The cost of
fabrication has not been considered.

MODULUS OF ELASTICITY

In view of the importance of modulus of elasticity in
design, this characteristic will be taken up at this time
prior to a discussion of the other items in which it is in-
volved and of the other properties of the two materials.

The elastic modulus of 24ST is 10,300,000 pounds per
square inch. This value is accepted by all designers and
well supported by many tests. The modulus of elasticity
of stainless steel of the 18-8 grade is not susceptible to

precise determination.   Some claim a modulus of 29,000,000
pounds per square inch for 18-8.   This figure is not sup-
ported by tests made at Wright Field, the Naval Aircraft
Factory, nor the National Bureau of Standards.   These
tests indicate the true elastic modulus to be approximate-
ly 26,000,000 and in some cases less.   Assuming that the
initial tangent modulus is 29,000,000, it would possibly
be satisfactory to use this figure where very small unit
stresses are involved but considering the range of stress-
es on the stress-strain curve for which the member would
be designed, good engineering practice dictates the use of
the lower value in the design of aircraft.   Like other
cold-rolled materials, the elastic modulus of 18-8 when
cold-worked and not subsequently annealed, is difficult to
define precisely because the stress-strain diagram of the
material is not a straight line but a curve whose curva-
ture begins practically at the origin.   Tests indicate,
however, that the curve can be straightened by suitable
annealing and by proper prestressing and the proportional
limit raised materially.   The effect of this prestretching
on other properties, especially fatigue and internal
stress, is being studied.

IMPACT

By the conventional methods of impact testing mate-
rial specimens at various temperatures, 18-8 appears def-
initely superior to 24ST.   Its impact resistance varies
from 35 to 29 ft.-lb. Charpy over a temperature range of
from room temperature to -80° C.   While test data on 24ST
are not available as yet, it is anticipated that the
Charpy value will not differ to any great extent from that
of the 17ST value which is approximately 10 to 9 ft.-lb.
(10 by 10 mm specimen keyhole notch, No. 47 drill).   Re-
sults of impact tests made on any one material over a
range of temperature are of value in determining the in-
fluence of temperature on that material.   Impact results
obtained with two or more materials differing widely in
weight and other physical properties, however, should not
be used as a basis of comparison of the suitability of the
two materials for use in aircraft construction.   In aero-
nautical service, the materials compete on a weight-saving
basis as well as on the basis of strength and work of de-
formation.

The present methods of impact testing although they

indicate what can be expected from a notched bar subjected to stresses to produce fracture, are not true indexes of the actual energy absorption power of materials. It is considered that the designer is more interested in the capacity of a member to resist injury when subjected to a suddenly applied load within or close to the elastic range than he is in the work done in fracturing the member. It is believed that resiliency, or elastic recovery from energy loads, would be more pronounced on materials of the same cross-sectional area with low moduli of elasticity than on those with high moduli when subjected to identical conditions of impact. The assumption is made that the work of deformation is equal to the energy of the blow. Considering the two formulas on page 42 of Johnson's "Materials of Construction" (reference 1) for stress under axial impact and for a beam under impact of a center load, it is apparent that the elastic modulus is a major consideration. These formulas are as follows:

$$W (h + e) = \frac{1}{2} \frac{S^2}{E} AL \qquad \text{(axial impact)} \qquad (1)$$

$$W (h + f) = \frac{1}{6} \frac{R^2}{C^2} \frac{S^2}{E} AL \quad \text{(center load)} \qquad (2)$$

W, weight falling

h, distance dropped

e, maximum deformation

S, maximum intensity of stress corresponding to deformation

E, modulus of elasticity

A, area of cross section

l, length

f, maximum deflection

It is therefore submitted that the tests on actual built-up structures, measuring deformation, and deflection under a suddenly applied load or by a drop test of the structure itself, are conducive of more accurate determinations of impact resistance within the range in which the designer is primarily interested than are the

Charpy or Izod methods of tests in common use. Under such
conditions the apparent differences in the impact resist-
ances of the materials as measured by the Charpy notched-
bar test will lose their significance in design.

FATIGUE

Cold-rolled 18-8 can usually be relied upon to devel-
op an endurance limit of slightly better than 50 percent
of its ultimate strength in tension. The endurance limit
of 24ST is approximately 14,500 pounds per square inch or
about 24 percent of its ultimate. In view of the differ-
ence in these fatigue ratios, it is apparent that where
fatigue alone is the controlling factor, 18-8 has the edge
where identical shapes are concerned. In comparing the
serviceability of two materials in structures subjected to
repeated stress, consideration should be given not only to
the fatigue limits but also to the stresses in a structure
designed on a weight-saving basis. For direct tensile
loading, on such a basis, steel evidently is superior to
aluminum alloys when the fatigue limit of the steel is more
than about three times that of the aluminum alloy. For re-
sistance to repeated bending or torsion, however, this 3
to 1 ratio does not apply. In order to be superior to an
aluminum alloy under repeated bending or torsion, the fa-
tigue limit of the steel must now be at least five times
that of the aluminum alloy.

INTERNAL STRESS

Materials such as cold-rolled corrosion-resistant
steel, which obtain their strength by strain hardening,
develop internal stresses as a result of this cold rolling.
It is a condition in which the outer layers of the mate-
rial are in a state of tension and the interior in a state
of compression. This condition does not exist in properly
heat-treated materials. In severely cold-worked 18-8,
i.e., 180,000 pounds per square inch and above, this inter-
nal tension stress may reach an enormously high value.
The objectionable features of such stresses are well known,
particularly when the material is subjected to even slight
corrosive attack. Tests conducted at the National Bureau of
Standards for the Bureau of Aeronautics on tie rods, reveal
that this stress in some cases was as high as 98,600 pounds

per square inch on 1050 steel and between 120,000 and
128,000 pounds per square inch on 18-8. In the presence
of such high internal stress, high tensile strengths in
cold-drawn materials such as 18-8 tie rods really serve
no good purpose for the higher the strength the greater
the internal stress. Further, tests indicate that high
tensile properties in such 18-8 are associated with mini-
mum torsional fatigue resistance, a property which should
be as high as possible compatible with adequate resistance
to corrosion fatigue for investigation discloses that the
majority of tie-rod failures have been due to torsional
fatigue. It has also been demonstrated that slight cor-
rosive attack will reduce the fatigue limit of materials
containing high internal stresses. In light of the fore-
going, it was concluded by the Engineering Experimental
Station at Annapolis, that nothing is to be gained by the
use of tie rods having a tensile strength greater than
160,000 pounds per square inch under conditions where tor-
sional fatigue is encountered. The torsional fatigue of
SAE 1050 steel and 18-8 tie rods is approximately the same
but the corrosion fatigue of the latter is definitely su-
perior. The corrosion-fatigue resistance of 18-8 was
found to be approximately 10,000 to 12,000 pounds per
square inch, whereas that of 1050 steel was about 7,000
pounds per square inch. The chief value of the former ma-
terial for tie-rod use therefore lies in its superior re-
sistance to corrosion fatigue.

In spite of the undesirable characteristics of corro-
sion-resistant steel and other strain-hardened steel for
tie-rod purposes, the adoption of 18-8 in lieu of 1050
steel appears to have been a sound and logical step in the
reduction of tie-rod failures. There are hundreds of air-
planes operating with 18-8 tie rods, on which no troubles
have been experienced. Accordingly, the material should
not be condemned for this use because of reported failures
on airplanes of known exceptionally high vibratory charac-
teristics. It is questionable whether SAE 1050 tie rods,
or tie rods made of other materials available in quantity,
would perform any better under such conditions. The search
for improved materials, preferably those which obtain their
strength from heat treatment, should, however, be contin-
ued. Preliminary tests indicate that the 16-percent chrome -
1-percent nickel alloy seems to have possibilities for this
use. This material obtains its strength from heat treat-
ment.

It is believed that the effect of internal stress in

thin sheet, although undesirable because of its indetermi-
nate value, is not of especial moment, but in rolled bar
such as used in the manufacture of tie rods, it should be
removed. That the internal stress can be removed without
adversely affecting the strength of the material, has been
demonstrated. Tests are continuing at the National Bureau
of Standards to determine and perfect the most practical
method of overcoming this undesirable condition and to as-
certain that this stress-relief treatment does not adverse-
ly affect other properties of the material, for the elim-
ination of one objectionable feature may be accomplished
at the expense of some other desirable property.

MAGNETIC PROPERTIES

Corrosion-resistant steel in the annealed condition
is practically nonmagnetic; however, cold-rolled to the
strengths required for aircraft applications, it is mag-
netic and affects the compass. This has been demonstrated
in service. 24ST aluminum alloy has no appreciable effect
on the compass.

EFFECT OF LOW TEMPERATURE ON PHYSICAL PROPERTIES

At low temperatures, i.e., $-80°$ C., cold-rolled 18-8
appears to behave like many other materials which obtain
their strength through strain hardening. Its tensile
strength increases considerably as the temperature de-
creases. In one test it increased from 130,000 to 175,000
pounds per square inch accompanied by an increase in elon-
gation. Its yield strength increases but slightly and in
some cases it has been found to decrease. Recent tests
conducted at the National Bureau of Standards for the Bu-
reau of Aeronautics indicate this to be the case and check
the results of tests on 18-8 reported in N.A.C.A. Technical
Note No. 381 (reference 2). In this report it was shown
that the yield strength dropped from a value of 114,600
pounds per square inch at room temperature to 112,400
pounds per square inch at $-40°$ C. The endurance limit in-
creases but the ratio of the endurance strength to the ul-
timate strength decreases. Impact resistance as deter-
mined by the Charpy method decreases generally with low
temperature but for the material in some conditions of
cold rolling it increases. Low temperature tests are now

being conducted on 24ST and the results to date indicate that it does not possess any peculiarly undesirable characteristics at low temperature.

CORROSION RESISTANCE

The corrosion resistance of stainless steel is considerably overemphasized. As compared with other unprotected high-strength alloy steels commercially available, it is, however, in a class by itself. Reports of examinations of airplanes in which stainless steel ribs were used and which have operated under severe conditions, indicate that it must be protected in some way to resist the attack of salt water. One report revealed that after but 182 hours of flight time, the ribs were found to be considerably corroded. Attack was so deep in some cases that it could not be removed without scraping with emery cloth. On the other hand, no serious corrosion trouble has been reported with the 18-8 external interplane tie rods probably because they are wiped down periodically and attack does not have the opportunity to get under way because of their accessibility and consequent relative ease of maintenance.

In comparison with anodically treated and painted aluminum alloy, free of contact with dissimilar metals and installed under adequate drainage conditions, and with consideration of the thin gages in which 18-8 would have to be used, the use of 18-8 in inaccessible places in aircraft operating off salt water is not considered good practice.

STRENGTH-WEIGHT

Stainless steel has a specific gravity of 7.92, aluminum alloy (24ST), 2.79. The weight ratio is therefore 2.84. Navy Department Specification 47A10 for 24ST specifies a minimum ultimate tensile strength of 62,000 pounds per square inch. Accordingly, to compete on an equal weight-strength basis, stainless steel members must develop a minimum tensile strength of not less than 176,080 pounds per square inch. This, stainless steel can easily do. A review of material inspection reports reveals that the ultimate of 24ST is approximately 64,000 pounds per square inch. The specification value will, however, be considered in this discussion.

On a yield-strength basis, assuming a yield of
160,000 pounds per square inch for stainless, which value,
tests indicate, can be obtained, and 40,000 for 24ST, its
specification value, the area of an aluminum alloy tension
member must be 4.00 times greater than that of the steel
member for the ratio of the areas of the cross section
vary inversely as the strengths. The ratio of weights will
be:

$$4 \times \frac{\text{(weight per cubic inch of 24ST)}}{\text{weight per cubic inch of 18-8}} = \frac{4 \times 0.101}{0.286} = 1.41$$

In other words, in pure tension, an aluminum alloy member
will weigh 41 percent more than a steel member to support
the same load.

COMPARISON OF TUBULAR BEAMS MADE OF 18-8 AND 24ST

Hartmann, whose assumptions appear sound, N.A.C.A.
Technical Note No. 378, (reference 3), shows that for
equal over-all weight and equal beam strength, ignoring
deflection, steel must have a yield strength 4.71 times
that of 17ST aluminum alloy to compete on a strength-weight
basis. Therefore considering, as before, the yield of 24ST
as 40,000 pounds per square inch, the steel would have to
develop a yield strength of 188,000 pounds per square inch.
This value is considerably in excess of the 160,000 pounds
per square inch value assumed for 18-8. This comparison
has been made on the basis that the yield strength of the
material is the limiting condition for the computed moduli
of rupture $\left(f = \frac{Mc}{I} \right)$ and that there is no restriction on
the outside diameter of the aluminum alloy member. In
this case, assuming a yield strength of 160,000 pounds per
square inch for the material in the stainless beam, the
aluminum alloy beam will be the lighter of the two. If,
however, size is a controlling factor, the aluminum alloy
beam is at a disadvantage, for in some cases it is not al-
ways practical from an aerodynamic or structural consider-
ation to spread the aluminum alloy out so that the metal
is working at its highest efficiency.

Considering equal deflections,

E (24ST) × I (24ST) = E (18-8) × I (18-8)

By following through the formula developed in refer-
ence 3)

$$d(24ST) = \left(\frac{2.60}{1.03}\right)^{1/4} \times d(18.8)$$

$$= 1.26 \, d(18-8)$$

$$d = \text{outside diameter}$$

i.e., for equal deflections with no limitations on the outside diameters, the outside diameter of the aluminum alloy tube must be at least 1.26 times the diameter of the steel tube. From the following formula the ratio of weights would be:

$$\frac{W(24ST)}{W(18-8)} = \frac{0.101}{0.286} \times \frac{d^2(24ST)}{d^2(18-8)}$$

$$= 0.36 \times 1.59$$

$$= 0.562$$

The aluminum beam, therefore, can be made 44 percent lighter than the steel tubular beam for the same span, load, and deflection when there is no restriction on the outside diameter.

If the outside diameters are kept equal, and assuming that the moduli of rupture are equal to the yield strengths, the inside diameters will vary as the yield strengths. The section modulus (I/c) of the aluminum alloy tube must be 4.00 times as great as the steel tube. Inasmuch as strength in bending is directly proportional to the section modulus multiplied by the unit stress, it can be readily shown that for equal strengths under this condition, steel definitely has the advantage on weight.

COMPARISON AS COLUMNS

A comparison of the two materials as columns would be an exhaustive study in itself for it involves a number of factors which should be considered for an accurate analysis. A review of the National Advisory Committee's reports on its investigation of thin-walled cylinders in compression is abundant evidence of the various factors involved. It can be concluded, however, that for short columns, steel has the weight advantage. In the long-column range, and provided there is no restriction on the

outside diameter, 24ST has a marked advantage over the
steel. Under such conditions the slenderness ratio of the
aluminum alloy member will be less than that of the steel,
and the material can be more economically distributed.
If, however, there is a restriction on the outside diame-
ter because of aerodynamic or structural considerations,
the steel tube will be the lighter of the two. No attempt
will be made to discuss the exact weight savings possible
by the use of either material under the conditions stated.
It is desired to point out, nevertheless, that the peculi-
arities of the stress-strain characteristics of 18-8, par-
ticularly in the elastic range, are not especially favor-
able to its use under axial compressive loads for it is not
a simple matter to predict whether the member will fail by
plastic yielding of local buckling. In other words, it ap-
pears extremely difficult to determine what d/t ratio
should be used to prevent local failure. Tuckerman, of the
National Bureau of Standards, in his recent Edgar Marburg
Lecture (reference 4), very ably sums up the problem by
saying: "However great the complications, the structural
problem of light-weight construction retains the same basic
character. It is the problem of securing the best possible
balance between plastic yielding, dependent upon the
strength density ratio of the material and major and local
elastic instabilities dependent upon its modulus density
ratio and finally the transitions between these, dependent
upon an accurate knowledge of its stress-strain curve."

STRESSED-SKIN COVERING

     In the case of stressed-skin structures, failure is
liable to result from local buckling. Under such condi-
tions the more rigid structure will as a rule withstand lo-
cal failure more satisfactorily than a thin structure of
relatively low rigidity. To compete on a weight basis,
high-strength steels must employ approximately one-third of
the material allowable for aluminum alloys. Although the
modulus of elasticity of such materials is about three
times that of the aluminum, the form factor, which is, to
a great extent, based on the bulk of the material used,
more than compensates for the difference in the inherent
rigidity. Fleetwings, Inc., has advocated carrying the
majority of the stress in stringers, using the skin largely
as a restraining influence on the stringers. This company
has designed and built stainless-steel wing structures of

reported high efficiency, using this scheme. It is be-
lieved, however, that the same ingenuity extended in the
direction of aluminum alloy would yield equally efficient
structures.

With the continued increase in speed, and the result-
ant increase in air pressures, it is believed that fabric
for wing covering will be eventually supplanted by metal
covering. The trend at present appears to favor the use
of metal, at least from the leading edge to the rear beam.
With the advent of metal covering it will be necessary to
choose between steel and aluminum for the entire wing
structure; for the use of composite structures of steel
and aluminum, because of corrosion hazard, is not the best
practice for severe operating conditions. That metal cov-
ering is definitely in the picture, cannot be denied.

All things considered, and in the absence of more ex-
tensive data on load-carrying capacities of stainless-
steel structures, it is believed that aluminum alloy at
present offers the best combination of properties for fab-
ricated structures of stiffened sheet and for columns.
For highly stressed fittings carrying lugs, good design
and psychological consideration point toward the use of
steel forgings, heat-treated subsequent to forging. Where
pure tension is the primary controlling factor, such as in
wires and cables, aluminum alloy obviously cannot compete
with other available materials. The structural advantages
of high-tensile steel for practically all primary applica-
tions, however, cannot be dismissed, even though it may re-
quire protection against corrosion. The optimum steel
should be one with a good stress-strain curve, uniformly
high mechanical properties, and properties capable of rea-
sonably accurate determination. Stainless steel, as it is
now available commercially, does not meet these require-
ments, and it is doubtful as to whether production methods
can be devised to make it so without increased expense to
the consumer. It is believed that the material should be
one which obtains its strength through heat treatment and
not through cold working.

Bureau of Aeronautics,
     Navy Department,
          Washington, D. C., March 1936.

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