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CRITICAL LOADING OF STRUCTURAL MEMBERS
SUBJECTED TO COMBINED AXIAL AND
TRANSVERSE LOADS

(AIRPLANE SECTION REPORT)

V

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[Signatures]
INTRODUCTION

The critical loading of a structure is defined as that load which will render the structure elastically unstable. It should be borne in mind that the critical loading is independent of the fiber stress. This means that, although rupture of the members involved may not occur, the structure will fail in the sense that any more load will cause excessive deflections regardless of the strength of the fiber. The critical load, then, is not the maximum load the structure will hold without rupture of the material, but the load causing excessive deflections or elastic instability.

The fibers of the material in a beam may be at the point of rupture because of bending stresses resulting from a side load before any axial load is applied. In this case it is obvious that the structure will fail when subjected to a very small axial load. This would not be called the critical load, but the maximum load. In general, we may consider the critical load as the upper limit of the axial load. That is, if a structure does not fail before this load is reached because of overstressed fibers, it will then fail because it becomes elastically unstable. It should be noted that the critical axial load for a beam under combined loading may be the same as the critical load for the beam without side load.

To illustrate the concept of instability as applied to a beam, we will consider in detail the behavior of a simple beam loaded uniformly and then subjected to an axial load. In Figure 1 (a) we have a beam AB of length L subjected to a side load of w pounds per inch. In Figure 1 (b) we have the elastic curve of the beam,

\[ y = \frac{1}{EI} \int \int M_{0} \, dx \]  

(1)

Since the effect of one load is independent of other loads on the beam, we may now assume, for the purpose of this illustration, that the beam has no side load, but instead has the initial curvature of equation 1. Now, if an axial load is applied as shown in Figure 2, an additional moment will be developed along the beam which will cause an additional deflection. We can easily obtain an analytic solution for the deflection, but it will be clearer if we obtain the result by successive approximations. For instance, if we substitute \( y_{0} \) for \( y \), and \( M_{0} \) for \( M_{1} \) in equation 1, and write the first approximation of the moment, which we will call \( M_{1} \), we have the absolute value.

\[ M_{1} = \left| P \frac{y_{0}}{EI} \right| \int \int M_{0} \, dx \]  

(2)

The absolute value of the deflection due to this additional moment, \( M_{1} \), is

\[ y_{1} = \left| \frac{1}{EI} \int \int M_{1} \, dx \right| \]  

(3)

The total deflection becomes

\[ y = y_{0} + y_{1} = \left| \frac{1}{EI} \int \int M_{0} \, dx \right| + \left| \frac{1}{EI} \int \int M_{1} \, dx \right| \]  

(4)

\[ = \left| \frac{1}{EI} \int \int M_{0} \, dx \right| + \frac{P}{EJ} \left| \int \int \int M_{0} \, dx \right| \]  

(5)

The moment due to the additional deflection \( y_{1} \) is

\[ M_{2} = \left| P \frac{y_{1}}{EI} \right| \int \int M_{0} \, dx \]  

(6)

and the additional deflection is

\[ y_{2} = \left| \frac{1}{EI} \int \int M_{2} \, dx \right| = \left| \frac{P}{EJ} \int \int \int \int M_{0} \, dx \right| \]  

(7)

\[ = \frac{P}{EJ} \left| \int \int \int \int M_{0} \, dx \right| \]  

(8)

The total deflection now becomes

\[ y = y_{0} + y_{1} + y_{2} + \cdots \]  

(9)

\[ = \left| \frac{1}{EI} \int \int M_{0} \, dx \right| + \frac{P}{EJ} \left| \int \int \int M_{0} \, dx \right| + \frac{P}{EJ} \left| \int \int \int \int M_{0} \, dx \right| \]  

(10)

Continuing in this manner we obtain the series

\[ y = \left| \frac{1}{EI} \int \int M_{0} \, dx \right| + \frac{P}{EJ} \left| \int \int \int M_{0} \, dx \right| + \frac{P}{EJ} \left| \int \int \int \int M_{0} \, dx \right| + \cdots \]  

(11)

These successive approximations are shown in Figure 3. It will be noted that the difference between the successive approximations becomes less and less, so that, if enough approximations are considered, the elastic curve can be found. However, in Figure 4 the axial load, \( P \), is of such magnitude that the successive increments of deflection are equal to or larger than the preceding increment. It is obvious in this case that no matter how often we repeat the process of finding the moment or deflection, we will never get a definite final result. This condition represents elastic instability. We conclude, therefore, that in order that
the structure remain stable, \( y_{n+1} \) must be less than \( y_n \), or \( y_{n+1} < y_n \). That is,

\[
y_{n+1} < y_n
\]

(12)

\[ M_s = \left[ \frac{M_1 - wL - (M_1 - wj^2) \cos \frac{L}{j} \sin \frac{x}{j}}{j} \right] \sin \frac{x}{j} + (M_1 - wj^2) \cos \frac{x}{j} + wj^2 \]

(13)

In this equation (see fig. 5),
- \( M_s \) is the moment between the supports.
- \( M_1 \) is the moment at \( x = 0 \).
- \( M_2 \) is the moment at \( x = L \).
- \( w \) is the loading, pounds per inch.
- \( j = \sqrt{\frac{E}{P}} \)
- \( P \) is the axial load.
- \( E \) is the modulus of elasticity.
- \( I \) is the moment of inertia of the cross-sectional area of the beam about a line through the neutral axis perpendicular to the plane of bending.

Rearranging equation 13 into a more convenient form, we have:

\[ M_s = \left[ \frac{M_1 \sin \frac{L}{j} (L-x) + M_1 \sin \frac{x}{j}}{j} \right] - wj^2 \sin \frac{x}{j} + \frac{wL}{j} \sin \frac{x}{j} \]

(14)

We will now investigate equation 14 for finiteness. If the numerator of the first term on the right-hand side of equation 14 is not zero and \( M_1 \) and \( M_2 \) are not infinite when \( \frac{L}{j} = \pi \), we have \( M_s = \text{infinity} \), as \( \sin \frac{L}{j} = 0 \).

But if

\[ \frac{L}{j} = \pi \sqrt{\frac{P}{EI}} \]

then

\[ P = \pi^2 \frac{EI}{L^2} \]

(16)

which is the criterion desired. This is Euler's critical load for a pin-ended strut. We can say in general, then, that the critical loading between the supports of a continuous beam is Euler's critical loading if the moments at the supports are known and if the numerator of the first term on the right-hand side of equation 14 is not zero.

While in equation 14 \( M_s \) may become infinite when \( \frac{L}{j} = \pi \), it does not mean that the beam will fail. It must be borne in mind that the beam is constrained to bend in a definite manner by the loading and moments, so that it does not always bend in the simplest type of curve. To illustrate this point, suppose a pin-ended strut without lateral load is held in such a manner that it bends in the curve shown in Figure 6 (a) instead of in the simpler curve shown in
Figure 6 (b). It is obvious that the strut does not fail when \( \frac{L}{j} = \pi \), though that is the first critical condition.

It is, therefore, apparent that \( \frac{L}{j} \) in equation 14 may pass through \( \pi \) without failure of the beam, though the numerator is not zero. The next critical point, in that case, will be at \( \frac{L}{j} = 2\pi \) unless \( M_1 \) or \( M_2 \) becomes infinite between \( \frac{L}{j} = \pi \) and \( 2\pi \). In general, however, one or the other of these moments will become infinite before this point is reached.

In Figure 7 (b), if there is a maximum, it will occur at the middle of the bay if \( M_1 = M_2 \), and the critical loading will be

\[
P = \frac{\pi^2 EI}{L^2}
\]

In case the moments at the three points of zero slope are equal, the critical loading will be given by the condition

\[
\cos \frac{L}{6j} = 0
\]

from which

\[
P = \frac{4\pi^2 EI}{L^2}
\]

\[
L = \frac{\pi}{4j}
\]

or

\[
P = \frac{4\pi^2 EI}{L^2}
\]

\[
M_1L_1a_1 + M_2L_2a_2 + M_1L_1b_1 + M_2L_2b_2 + M_1L_1a_2 + M_2L_2a_2
\]

\[
= \frac{wL_1^3}{4I_1} + \frac{wL_2^3}{4I_2}
\]

We will now consider the case in which \( M_2 \) becomes infinite. We have the general three-moment equation

\[
M_1L_1a_1 + M_2L_2a_2 + M_1L_1b_1 + M_2L_2b_2 + M_1L_1a_2 + M_2L_2a_2
\]

\[
= \frac{wL_1^3}{4I_1} + \frac{wL_2^3}{4I_2}
\]

We will assume that \( M_1 \) and \( M_2 \) are due to a cantilever overhang and are independent of the axial load. See Figure 5. Solving for \( M_2 \) in equation 25 we have:

\[
M_2 = \frac{M_1L_1b_1 + M_2L_2b_2}{L_1^2/2 + L_2^2/2}
\]

We now inquire into the conditions which make \( M_2 \) infinite. \( M_2 \) will be infinite when the denominator is zero, provided the numerator is not zero. If the numerator is zero, \( M_2 \) is zero, and, therefore, finite. In order that the denominator become zero, we have

\[
L_1/\beta_1 + L_2/\beta_2 = 0
\]

We now inquire into the conditions which make \( M_2 \) infinite. \( M_2 \) will be infinite when the denominator is zero, provided the numerator is not zero. If the numerator is zero, \( M_2 \) is zero, and, therefore, finite. In order that the denominator become zero, we have

\[
L_1/\beta_1 + L_2/\beta_2 = 0
\]

Since \( I \) and \( L \) are always positive, we have the critical load occurring when \( \beta_2 \) has the opposite sign to \( \beta_1 \).

The criterion expressed in equation 27 is easily interpreted, because the values of \( \beta \) are tabulated in the above-mentioned report. \( \beta \) changes sign through infinity at \( \frac{L}{j} = \pi \) and through zero at \( \frac{L}{j} = 4.49 + \) radians.
At \( \frac{L}{j} = \pi \), \( \alpha \), \( \beta \), and \( \delta \) all become infinite. In this region, then, there is a possibility that equation 26 merely becomes "indeterminate," and may be evaluated. At \( \frac{L}{j} = 4.49 \), \( \alpha \) and \( \delta \) do not become zero or infinite, so that this is a region of a critical point, since \( \beta \) changes sign and \( \frac{L}{j} \) becomes equal to \( -\frac{L}{j} \) in this neighborhood.

The value of \( M_2 \) in the region of \( \frac{L}{j} = \pi \) requires special consideration. In equation 26 we note that \( \alpha_1, \beta_1, \delta_1 \), or \( \alpha_2, \beta_2, \delta_2 \) become infinite together. If \( \beta_1 \) is not equal to \( \beta_2 \), then when \( \beta_1 \) is infinite, \( \alpha_2, \delta_2 \), and \( \beta_2 \) are finite. We note that if \( M_2 \) is determinate when \( \beta_1 \) passes through infinity at \( \frac{L}{j} = \pi \), it is also determinate when \( \frac{L}{j} \) passes through \( \pi \). It is thus determinate when \( \beta_1 \) and \( \beta_2 \) pass through infinity together. We will consider the case in which \( \beta_1 \) passes through infinity and \( \beta_2 \) is finite. We have from equation 26, by writing out the values of \( \alpha_1, \beta_1, \delta_1 \), and \( \alpha_2, \beta_2, \delta_2 \),

\[
\frac{w_1 L_1}{4 I_1} \left[ \frac{3 \left( \tan \frac{L_1}{j} \beta_1 \right)^2}{I_1} \right] M_1 L_1 + \frac{w_1 L_1^2}{4 I_1^2} a_2 - \frac{M_1 L_1}{I_1} \left[ \frac{6 \left( \frac{L_1}{j} \cot \frac{L_1}{j} \right)^2}{I_1} \right] M_1 L_1 \left[ \frac{3 \left( \frac{L_1}{j} \cot \frac{L_1}{j} \right) x}{I_1} \right] + \frac{M_1 L_1}{I_1} \left[ \frac{3 \left( \frac{L_1}{j} \cot \frac{L_1}{j} \right) x}{I_1} \right] \left( \frac{L_1}{j} \beta_1 \right) \]

We note that when we substitute \( \pi \) for \( \frac{L}{j} \) in this equation we obtain the "indeterminate" quantity \( \infty \). To investigate for finiteness we take the derivative of the numerator with respect to \( \frac{L}{j} \) for a new denominator and the derivative of the numerator with respect to \( \frac{L}{j} \) for a new numerator. We note that when this is done all denominators involving the subscript 2 drop out, and \( \frac{L_1}{j} \) cancels out. If we let \( \frac{L_1}{j} = \pi \) for ease in handling, we have the equivalent expression to consider:

\[
\frac{w_1 L_1}{4 I_1} \left[ \frac{24 \left( \tan \frac{x}{2} \right)^2}{x^2} \right] - M_1 \left[ \frac{6 \left( x \cot x \right)}{x^2} \right] = \frac{w_1 L_1}{4 I_1} \left[ \frac{4 \left( \tan \frac{x}{2} \right)}{x} \right] - M_1 \left( x \cot x - 1 \right) \]

\[
\frac{4 w_1 L_1^2 \tan \frac{x}{2}}{x^2} - 4 \frac{w_1 L_1}{I_1} M_x \cos x + M_1 \]

\[
\frac{4 w_1 L_1^2 \tan \frac{x}{2}}{x} - \frac{4 w_1 L_1^2}{I_1} M_x \cos x + M_1 \]

Taking the derivatives of the numerators and denominators with respect to \( x \), we have for the first term:

\[
\frac{4 w_1 L_1^2 \tan \frac{x}{2}}{x^2} - \frac{4 w_1 L_1^2}{I_1} M_x \cos x + M_1 \]

Since \( \sin \frac{x}{2} \cos x \) in the numerator is equal to \( -1 \) when \( x = \pi \), and \( \frac{1}{2} x^2 \sin \frac{x}{2} \cos x \) in the denominator is equal to \( -\frac{1}{2} x^2 \), the first term is determinate and is thus not infinite.

It is thus clear that when \( \frac{L}{j} \) passes through the value of \( \pi \), \( M_2 \) remains finite. However, since \( \beta_1 \) and \( \beta_2 \) must have opposite signs, the value of \( \frac{L}{j} \) for one bay must be less than \( \pi \), while the value for the other bay must be greater than \( \pi \). It is thus evident that the Euler load may be exceeded in certain bays of a continuous beam, provided this load is not reached in certain other bays.

The question now is: How can we determine whether we have reached the critical loading for the combination of two bays? To do this we calculate \( \frac{L}{j_1} \) and \( L_2 \) and then take \( \beta_1 \) and \( \beta_2 \) from the table of these functions. If both \( \beta_1 \) and \( \beta_2 \) are positive, the critical load is not exceeded. If both are negative, the critical load is exceeded unless \( \beta_1 = \beta_2 \). If \( \beta_1 \) is positive and \( \beta_2 \) is negative and the absolute values have the relation

\[
\left| \frac{L}{j_1} \beta_1 \right| < \left| \frac{L}{j_2} \beta_2 \right| \]

then the critical loading for both bays has not been reached.
If $\beta_1$ is positive and $\beta_2$ is negative and the absolute values have the relation
\[
\left| \frac{L_1}{I_1} \beta_1 \right| > \left| \frac{L_2}{I_2} \beta_1 \right| \tag{36}
\]
the critical loading for both bays has been passed.

This may also be expressed in the following manner:
If $\beta_1$ and $\beta_2$ are of opposite signs, a positive algebraic sum indicates that the critical load has been passed, while a negative algebraic sum indicates that the critical load has not been reached.

This last criterion is illustrated graphically in Figure 8. Curves showing $\frac{L_1}{I_1} \beta_1$ in the positive region, between $\frac{L}{j} = 0$ and $\frac{L}{j} = \pi$, and of $\frac{L_2}{I_2} \beta_2$ in the negative region, between $\frac{L}{j} = \pi$ and $\frac{L}{j} = 4.49 +$, have been drawn.

For the purpose of comparison with the positive values of $\frac{L_1}{I_1} \beta_1$, the absolute values of $\frac{L_2}{I_2} \beta_2$ are indicated by a dashed line. Suppose we consider the value of $\frac{L_1}{I_1} \beta_1$ at $A$ and the value of $\frac{L_2}{I_2} \beta_2$ at $B$. Since the absolute values are equal, we have a point of critical loading. Now, if the length of either bay is shortened, or the axial load $P$ is decreased, the two bays will be strengthened and the loading will then be below the critical loading. A decrease in either $L$ or $P$ causes a decrease in $\frac{L}{j}$. We note, then, from Figure 8, that this indicates a decrease in $\frac{L_1}{I_1} \beta_1$, but an increase in $\frac{L_2}{I_2} \beta_2$. That is, the absolute value of the negative quantity becomes greater than the value of the positive quantity. The algebraic sum, therefore, which will be negative, indicates that the critical load has not been reached. An increase in the length of either bay, or in the axial load, will result in a positive algebraic sum, which obviously indicates that the critical point has been passed.

One special case deserves attention. This is the case considered on page 17 of McCook Field Serial Report No. 2400, Air Service Information Circular 493. Here we have $L_1 = L_2$, $I_1 = I_2$, and $\beta_1 = \beta_2$, so that $\beta_1$ and $\beta_2$ pass through infinity at $\frac{L}{j} = \pi$ at the same time. $M_2$ is determinate, so that $\beta_1$ and $\beta_2$ do not have opposite signs until $\frac{L}{j} = 4.49 +$ is reached. While this indicates the correct critical loading, the configuration of the beam is not of the simplest form, so that it would probably be very unstable after $\frac{L}{j} = \pi$ is reached.

**BEAM WITH THREE BAYS**

We will now consider the critical loading of a beam with three bays as shown in Figure 9. The symmetrical condition is that found in airplane spars continuous through the span. We have $M_1 = M_0$, $M_2 = M_3$, $L_1 = L_3$, $I_1 = I_3$, and $w_1 = w_3$. 

![Figure 9](image-url)
From the general three moment equation we have:

\[
M_3 L_3 \alpha_1 + 2 M_2 L_2 \beta_2 + M_1 L_1 \alpha_1 = \frac{w_1 L_1^3}{4 I_1} \beta_1 + \frac{w_2 L_2^3}{4 I_2} \beta_2
\]

Since \( M_3 = M_1 \),

\[
M_3 = \frac{w_1 L_1^3 \beta_1 + w_2 L_2^3 \beta_2 + M_1 L_1 \alpha_1}{I_1}
\]

Thus,

\[
M_3 = \frac{w_1 L_1^3 \beta_1 + w_2 L_2^3 \beta_2 + M_1 L_1 \alpha_1}{I_1} - \frac{2 M_2 L_2 \beta_2}{I_2} + \frac{M_1 L_1 \alpha_1}{I_1} = \frac{M_1 L_1 \alpha_1}{I_1}
\]

We note that the denominator becomes zero when

\[
3 \frac{L_2}{I_2} + 2 \frac{L_2}{I_1} \beta_1 = - \frac{L_2}{I_1} \left( \frac{L_2}{I_2} \right)^2 \delta_1 + 3 \frac{L_2}{I_1}
\]

Since the constants of the equation can not be negative, a critical condition develops at a point where \( \beta_1 \) and \( \delta_1 \) have opposite signs. A perusal of the table of these functions will show that they both change sign through infinity at \( \frac{L}{I} = \pi \).

We thus have the following criterion:

If \( \beta_1 \) and \( \delta_1 \) are both positive, the beam has not reached a critical point.

If \( \beta_1 \) and \( \delta_1 \) are both negative, the first critical point has been passed except for the special case when \( \delta_1 = \beta_1 \).

If \( \beta_1 \) and \( \delta_1 \) have opposite signs, we have two cases with which to deal; that is, when \( \delta_1 \) is negative and when \( \beta_1 \) is negative. When \( \beta_1 \) is negative we have the condition shown in equation 41. A graphical representation of the condition is shown in Figure 10. The absolute value of \( \frac{L_2}{I_2} \left( \frac{L_2}{I_2} \right)^2 \delta_1 \) is indicated by the dashed line for the purpose of comparison with the positive values of the \( \beta_1 \) term. If we consider the points \( A \) and \( B \), we note that equation 41 becomes zero at this value of the ordinate, so that the line \( AB \) represents a critical condition. Now, suppose we hold the length of bay 2 (see fig. 9) constant, and shorten bay 1. Since \( L_3 = L_1 \), we also shorten \( L_3 \). This obviously has a strengthening effect on the structure. But with reference to Figure 10, we note that since \( \frac{L_2}{I_2} \) is constant and \( L_1 \) and \( L_1 / I_1 \) are decreased, the sum \( 3 \frac{L_2}{I_2} \frac{L_1}{I_1} \beta_1 \) is decreased. This indicates that the algebraic sum of the terms \( 3 \frac{L_2}{I_2} \frac{L_1}{I_1} \beta_1 \) and \( \frac{L_2}{I_2} \left( \frac{L_2}{I_2} \right)^2 \delta_1 \) is negative. We say, then, that when this sum is negative the critical loading has not been reached, and when it is positive the critical load has been passed.

When \( \beta_1 \) is negative and \( \delta_1 \) is positive we have

\[
3 \frac{L_2}{I_2} \frac{L_1}{I_1} \beta_1 = - \frac{2 L_2}{I_1} \beta_1
\]

This equation is shown in graphical form in Figure 11. As before, the line \( AB \) represents the critical condition. Since a decrease in the length of either bay has a strengthening effect, we note from the chart that this requires the negative value to increase absolutely and the positive value to decrease. Thus, when the algebraic sum of the terms in equation 42 is negative, the critical load has not been reached, and when the sum is positive, it has been passed.

As a special example, suppose \( L_1 \) and \( L_2 \) are zero. We have, then, an Euler strut fixed at the ends, the critical loading of which, as is generally known, occurs when \( \frac{L}{I} \) equals \( 2 \pi \). We obtain this same result from equation 41, for we have

\[
3 \frac{L_2}{I_2} = - \frac{L_2}{I_2} \left( \frac{L_2}{I_2} \right)^2 \delta_2
\]

or

\[
\delta_2 = \frac{1}{2} \left( \frac{L_2}{I_2} \right)^2
\]
section of the two curves. Values of \( \frac{L}{f} \) may be assumed, the right-hand side of the equation calculated, and the left taken from the table of functions. This method can also be used in solving equations 27 and 41, thus obtaining the value of \( \frac{L}{f} \) for the critical loading.

**CONCLUSIONS**

We note from the preceding discussion that, with the exceptions of certain special cases, we may determine for a two or a symmetrical three bay spar whether the critical load has been reached or passed by the following criteria:

**Two-bay spar, cantilever overhang**

<table>
<thead>
<tr>
<th>Condition</th>
<th>Loading</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \beta_1 ) and ( \beta_2 ) both positive</td>
<td>Safe.</td>
</tr>
<tr>
<td>( \beta_1 ) and ( \beta_2 ) both negative</td>
<td>Unsafe.</td>
</tr>
<tr>
<td>( \beta_1 ) and ( \beta_2 ) of opposite signs, algebraic sum ( \frac{L_1}{L_2} \beta_1 + \frac{L_2}{L_1} \beta_2 ) negative</td>
<td>Safe.</td>
</tr>
<tr>
<td>( \beta_1 ) and ( \beta_2 ) of opposite signs, algebraic sum ( \frac{L_1}{L_2} \beta_1 + \frac{L_2}{L_1} \beta_2 ) positive</td>
<td>Unsafe.</td>
</tr>
</tbody>
</table>

**Symmetrical three-bay spar, cantilever overhang (as specified in Figure 9, exclusively)**

<table>
<thead>
<tr>
<th>Condition</th>
<th>Loading</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \beta_1 ) and ( \delta_1 ) both positive</td>
<td>Safe.</td>
</tr>
<tr>
<td>( \beta_1 ) and ( \delta_1 ) both negative</td>
<td>Unsafe.</td>
</tr>
<tr>
<td>( \beta_1 ) and ( \delta_1 ) of opposite signs, and algebraic sum ( 3 \frac{L_1}{L_2} + 2 \frac{L_2}{L_1} \delta_1 ) is negative</td>
<td>Safe.</td>
</tr>
<tr>
<td>( \beta_1 ) and ( \delta_1 ) of opposite signs, and algebraic sum ( 3 \frac{L_1}{L_2} + 2 \frac{L_2}{L_1} \delta_1 ) is positive</td>
<td>Unsafe.</td>
</tr>
</tbody>
</table>