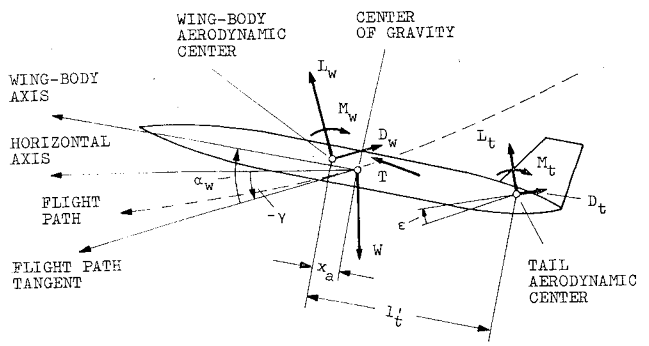

Fig. 1 Forces and moments.

Here terms of small order are neglected too, such as the differences in the effects of drag as well as thrust on pitching moment, acceleration and damping effects or the change in wing-body pitching-moment coefficient at $C_{Lw} = 0$. In consequence of appropriate choice of α_w (i.e., the wing-body reference axis) x_a the effective lever arm of ΔC_{Lw}.

The change in pitching-moment coefficient due to ground effect in case of constant elevator angle ($\Delta\delta_e = 0$) is, from (3),

$$\Delta C_m = \frac{x_a}{\bar{c}}\, \Delta C_{Lw} - k_t \frac{l'_t}{\bar{c}} \left(1 - \frac{x_a}{l'_t}\right) \Delta C_{Lt}|_\delta \qquad (4a)$$

or, using the measured values of the change in elevator angle,

$$\Delta C_m = k_t \frac{l'_t}{\bar{c}} \left(1 - \frac{x_a}{l'_t}\right)(a_{t_0} + \Delta a_t)\Delta\delta_e \qquad (4b)$$

The change in tail lift coefficient in case of constant elevator angle is given by

$$\Delta C_{Lt}|_\delta = \Delta a_t(\alpha_t - \epsilon_0 + \tau\delta_{e0}) - (a_{t_0} + \Delta a_t)\Delta\epsilon \qquad (5)$$

The initial steady-state conditions are

$$C_{Lw_0} \doteq C_{L0} - k_t C_{Lt_0} \qquad (6)$$

$$C_{Lt_0} = a_{t0}(\alpha_t - \epsilon_0 + \tau\delta_{e0}) \qquad (7)$$

and

$$C_{m0_w}{}^* + \frac{x_a}{\bar{c}}\, C_{Lw_0} - k_t \frac{l'_t}{\bar{c}} \left(1 - \frac{x_a}{l'_t}\right) C_{Lt_0} = 0 \qquad (8)$$

where $C_{m0_w}{}^*$ includes effects of drag and thrust on pitching moment.

With the use of these equations and on the assumption that τ is constant, the change in pitching-moment coefficient is found to be

$$\Delta C_m = \frac{x_a}{\bar{c}}\, C_{Lw_0} \left[\frac{\Delta C_{Lw}}{C_{Lw_0}} - \frac{\Delta a_t}{a_{t0}} - k_t a_{t0} \left(1 + \frac{\Delta a_t}{a_{t0}}\right) \times \frac{\Delta\epsilon}{C_{Lw_0}}\right] + k_t \frac{l'_t}{\bar{c}}\, a_{t0} \left(1 + \frac{\Delta a_t}{a_{t0}}\right) \Delta\epsilon - \frac{\Delta a_t}{a_{t0}}\, C_{m0_w}{}^* \qquad (9a)$$

or, since from (1) and (3)

$$\Delta C_{Lw} = \left(1 - \frac{x_a}{l'_t}\right) \Delta C_L$$

it can be expressed as

$$\Delta C_m = \left(1 - \frac{x_a}{l'_t}\right) \left\{ C_{L0} \left[\frac{x_a}{\bar{c}} \left(\frac{\Delta C_L}{C_{L0}} - \frac{\Delta a_t}{a_{t0}}\right) + k_t \frac{l'_t}{\bar{c}}\, a_{t0} \left(1 + \frac{\Delta a_t}{a_{t0}}\right) \frac{\Delta\epsilon}{C_{L0}}\right] - \frac{\Delta a_t}{a_{t0}}\, C_{m0_w}{}^* \right\} \qquad (9b)$$

An approximation can be derived from (9b), if $\Delta a_t/a_{t0} \ll \Delta C_L/C_{L0}$ (i.e., the tail is not too close to the ground in comparison with the wing) and $C_{m0_w}{}^*$ is not too large compared with C_{L0}. As in addition x_a/l'_t is usually small ($x_a/l'_t \ll 1$), it follows that

$$\Delta C_m \doteq C_{L0} \left(\frac{x_a}{\bar{c}}\, \frac{\Delta C_L}{C_{L0}} + k_t \frac{l'_t}{\bar{c}}\, a_{t0} \frac{\Delta\epsilon}{C_{L0}}\right) \qquad (10)$$

Examination of (9) and (10) shows the main factors causing a change in pitching-moment coefficient due to ground effect: the reduction in downwash angle at the tail $\Delta\epsilon$, and the increase in lift of wing-body combination ΔC_{Lw} and in tail lift slope Δa_t combined with the position of center of gravity x_a.

Usually, when ΔC_{Lw} and $\Delta\epsilon$ are the dominant parameters, the most negative change in pitching-moment coefficient occurs for the most forward position of center of gravity because the factor of $x_a/\bar{c}$ in (9a) and (10) is positive.

Being sufficiently large, the terms containing x_a may equalize the remaining ones because their effects on ΔC_m are opposite in case of different signs. Thus, it is possible, that the change in pitching-moment coefficient is negligible and a change in elevator angle is not necessary for a constant-angle-of-attack approach.

ΔC_m is also a function of the initial steady-state lift coefficient C_{L0}. Its absolute value usually increases with an increase in C_{L0}. In case of no significant change in $\Delta C_L/C_{L0}$, $\Delta\epsilon/C_{L0}$ and $\Delta a_t/a_{t0}$ due to variation of C_{L0}, it follows that ΔC_m is essentially a linear function of C_{L0}.

References

[1] Schweikhard, W., "A Method for In-Flight Measurement of Ground Effect on Fixed-Wing Aircraft," *Journal of Aircraft*, Vol. 4, No. 2, March-April 1967, pp. 101–104.

[2] Sachs, G., "Erweiterung eines neuen Verfahrens zur Bestimmung des Bodeneffekts aus Flugversuchen," *Zeitschrift für Flugwissenschaften*, Band 17, Heft 7, 1969, pp. 242–248.

Fail-Safe Criteria and Analysis of VTOL Dynamic Component Structures

M. J. Rich*
Sikorsky Aircraft, Division of United Aircraft Corporation, Stratford, Conn.

I. Introduction

PRESENT practice requires factors of safety such as 1.5 for static limit stresses and some reduction from the mean fatigue strength to insure that failure is remote from the operating loads environment. However, in addition to the mentioned factors of safety, greater emphasis is now being placed on the ability to operate safely under conditions where damage has been imparted to the structure. For example, the tentative[1] airworthiness standards of the Department of Transportation requires that an assessment of the residual fatigue strength after a partial failure must be made, and furthermore, permits an analytical assessment to be acceptable where such methods are shown to be reliable. Alternately, the VTOL manufacturer will be faced with test verification for each of the structural components deemed a safety of flight item.

II. Fail-Safe Design Criteria

The design criteria for VTOL aircraft must encompass both the static residual strength and the crack propagation

Submitted February 7, 1969; presented as Paper 69-214 at the AIAA/AHS VTOL Research, Design, and Operations Meeting, Atlanta, Ga., February 17–19, 1969; revision received July 10, 1969.

* Assistant Branch Chief, Structures and Materials Research and Development.

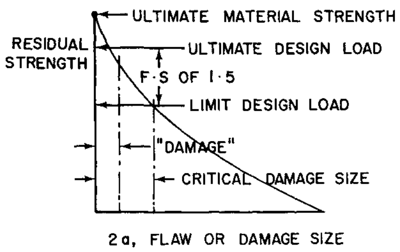

Fig. 1 Residual strength.

time for the damaged structure. Fracture mechanics methods have been developed for assessment of the residual strength of the damaged structure based on the amount of flaw size.

The residual strength of the damaged structure should be such that, for the anticipated damage, the remaining load capability is not less than the limit design loading. In Fig. 1, the material ultimate strength and limit design load are shown in relationship to the damage. The usual factor of safety of 1.5 will permit an appreciable flaw or damage to exist without resulting in a self-propagating crack.

The initial crack size will increase with time for vibratory loadings. The dynamic loading is generally much lower than

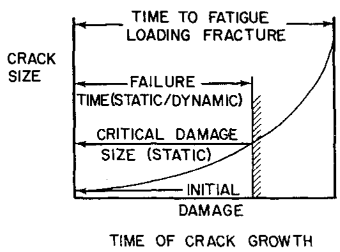

Fig. 2 Crack growth time.

the static loading, and the time to fatigue loading fracture may not present the total picture of the problem. Depending on the material, the limit on the fatigue crack growth time can well be reaching the critical crack size that causes a static failure. Thus, as is illustrated in Fig. 2, the failure time may be limited by reduction of residual strength below the limit loading requirement. While this may be a conservative approach in that the probability of reaching limit load is remote, the criteria does provide a consistent approach for the fail-safe criteria.

III. Analysis of Materials and Structures

Methods of analysis now permit an analytical assessment of the static residual strength and crack propagation time for a damaged structure.[2] For example, the static residual strength of various aircraft materials is shown in Fig. 3.

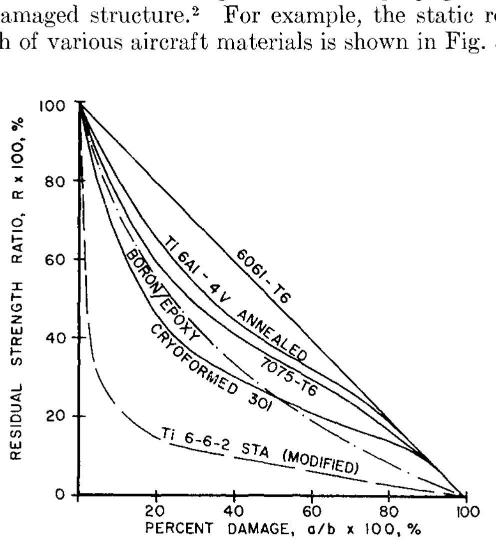

Fig. 3 Residual strength of various materials.

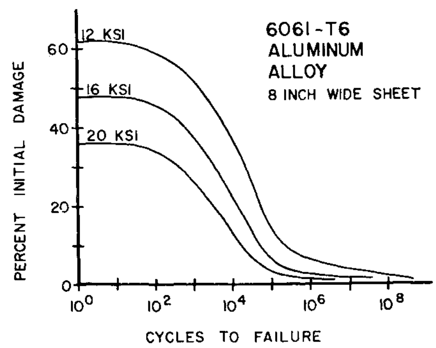

Fig. 4 Effect of stress on cycles to failure.

The residual strength remaining as illustrated in Fig. 3 would at first indicate a definite choice for the designer. However, the selection at least on a static strength basis, is dependent on how much of the material strength is used in design as well as the effectiveness of the choice on a weight basis. For example for a ten percent damage, the residual strength/weight for cryoformed 301 SS is 50% higher than for 6061-T6. In addition, since there are dimensional

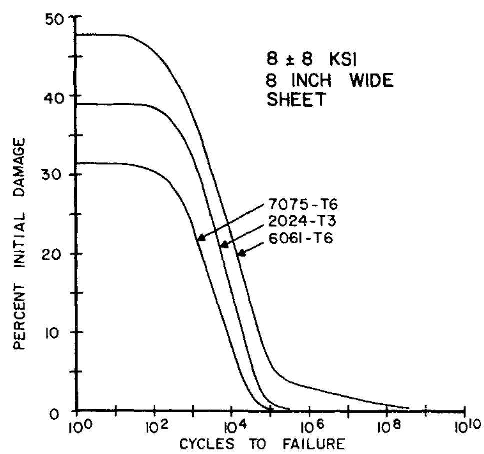

Fig. 5 Effect of alloy on cycles to failure.

effects, the residual strength diagram should be made for the particular geometry of the structure.

The dynamic residual strength is expressed as the crack propagation time for an initial damage or crack. The greater the initial damage, the less propagation time remains for the structural element. Examples of analysis on the effect of initial damage are shown in Fig. 4 for 6061-T6 with varying stress levels and in Fig. 5 at the same stress levels for different aluminum alloys. For these comparisons, a minimum to maximum stress ratio of zero has been used.

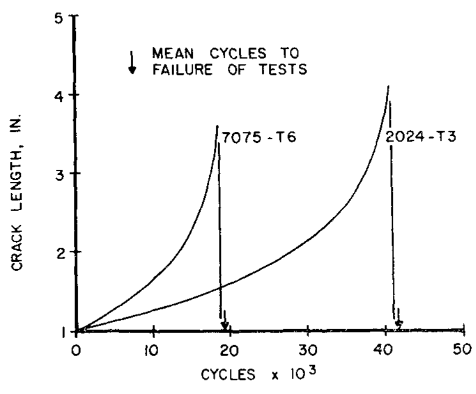

Fig. 6 Comparison of theory and tests, crack propagation with 1-in. initial damage.

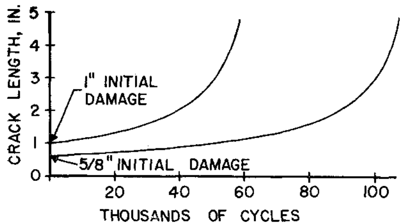

Fig. 7 Predicted propagations of a damaged 6061-T6 main rotor blade.

Since the comparison is only for a set of dimensional conditions and stress ratios, a definite conclusion on the selection of a material for a structural element cannot be made. However, the comparison does offer the designer a guide, and for a particular structure the designer should make up his own parameters to permit a design selection.

A comparison of the analytical methods with test data[3] shows good agreement with the mean time for crack propagation to failure for specific damage. In Fig. 6, a comparison is made for 2024-T3 and 7075-T6 for an initial damage size of 1 in.

As an extension to the simple sheet structure, a 6061-T6 blade spar with variable stress distribution has been analyzed.[2] Initial damage size from $\frac{5}{8}$–1 in. was used in Fig. 7 for a comparison with component testing. The damage band and the mean time to failure have shown correlation to be within 10% of test results. Figure 7 illustrates the necessity of being able to determine the damage at an early stage.

IV. Summary

In summary, methods are available that provide an analytical solution for the static residual and fatigue dynamic strengths. The criteria for damage shows that both static and dynamic considerations are required to establish a fail-safe analysis procedure. Good correlation between theory and test has been shown for a specific component and type of damage. However, additional testing is needed to verify and/or modify theoretical analysis of more complex components.

V. References

[1] "Tentative Airworthiness Standards for Verticraft/Powered Lift Transport Category Aircraft," July 1968, Department of Transportation, Federal Aviation Administration, Washington, D.C.

[2] Rich, M. J. and Linzell, L. E., "Damaged Static and Fatigue Stress Analysis of VTOL Structures," AIAA Paper 69-214, Atlanta, Ga., 1969.

[3] Degnan, W. G., Dripchak, P. D., and Matusovich, C. J., "Fatigue Crack Propagation in Aircraft Materials," Rept. 66-9-Contract DA-177-AMC-256(T), March 1966, U.S. Army Aviation Materials Lab., Fort Eustis, Va.