Tension Analysis of Stiffened Aircraft Structures

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Abstract

An analysis method is presented for a mechanically fastened built-up structure under tension load. The strain concentration at failure is determined experimentally using a small fastener specimen and is utilized to relate the tension strength to the material stress-strain curves and the geometry of the structure. Large panel tests are used to verify the analysis method.

Contents

The failure of a mechanically fastened structure occurs when the strain at the edge of one of the fastener holes, in the critical element of the structure, reaches the material's local strain capability. However, the material that reaches this strain capability is very localized. For a typical built-up structure, with small hole-out, the nominal strain at failure is just beyond the material yield strain.

In the past, the tension strength of a stiffened structure was related to the ultimate material failure stress. An efficiency factor was used to account for the stress concentration. The proposed analysis method shows that the tension strength of typical stiffened structure with small hole-out is strongly influenced, instead, by the material yield stress. This analysis requires stress-strain curves for the skin and stringer materials and the strain concentation factor at failure of the critical element (the element with the least elongation capability). The strain concentration factor is the ratio of the material strain (determined from standard tensile coupons) divided by the structural element strain at failure. Small specimens containing a row of fasteners are used to determine the structural element strain (change in length divided by the original length of the element) at failure. These small fastener specimens must have the same percentage hole-out and same fastener system, thickness, and edge margin as the structural element.

The method of determining tension strength is illustrated in Fig. 1. The skin and stringer stress-strain curves are shown with the skin assumed as the critical element. The same approach would apply if the stringer were the critical element. The panel failure strain is determined by dividing the total material strain to failure by the strain concentration factor of the critical element. The total (elastic plus plastic) strain is consistently used. At failure, the nominal net area stresses are just above the material yield stress with the local stress at the edge of the hole in the critical element reaching the material ultimate stress. These variations are shown by the heavy lines in Fig. 1. The exact load capability of the panel could be determined by integrating the failure stresses over the net areas. However, since an analytical solution for the net area failure stress is not available, an approximate but conservative method is used. The failure gross area stress (f_t) is computed using the expression

$$f_t = (A_{en} f_{te} + A_{sn} f_{ts}) / (A_{eg} + A_{sg}) \tag{1}$$

where A_{en} and A_{eg} are the net and gross areas of the stringers, A_{sn} and A_{sg} are the net and gross areas of the skin, and f_{te} and f_{ts} are the stringer and skin net area stresses at the panel failure strain, respectively. Equation (1) is conservative in that it neglects slightly higher stresses near the fastener holes. However, this effect is very small for a typical structure with small percentage hole-out.

The panel gross area allowable stress (F_t) is determined based on the same procedure except that the "standard material stress-stain curves" for the appropriate design basis are used. The "standard material stress-strain curve" is developed based on the material allowable yield and ultimate stresses (normally 90% reliability, 95% confidence, "B" basis), the typical modulus of elasticity, and plastic elongation using the Strain Departure Method of MIL-HDBK-5D. The equation for determining the panel gross areas allowable stress (F_t) is

$$F_t = (A_{en} F_{te} + A_{sn} F_{ts}) / (A_{eg} + A_{sg}) \tag{2}$$

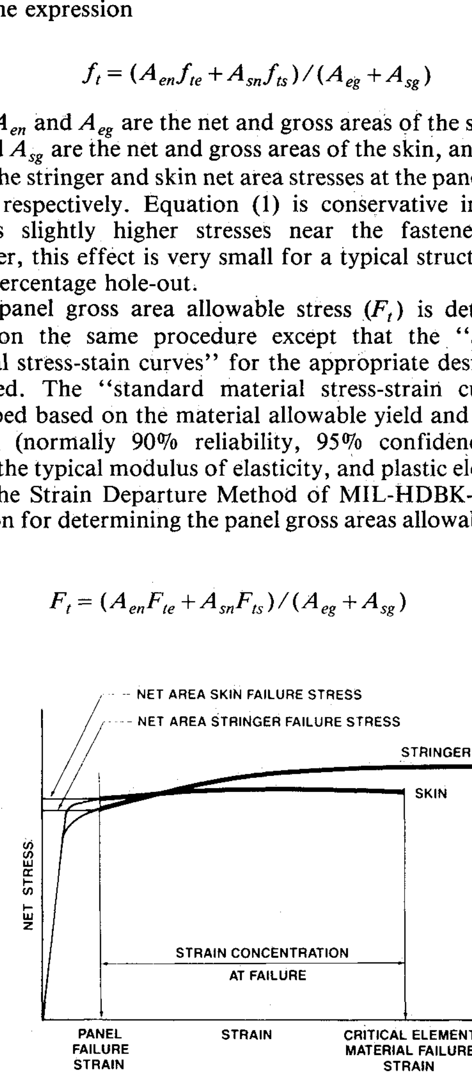

Fig. 1 Proposed method of determining tension strength for stiffened panels.

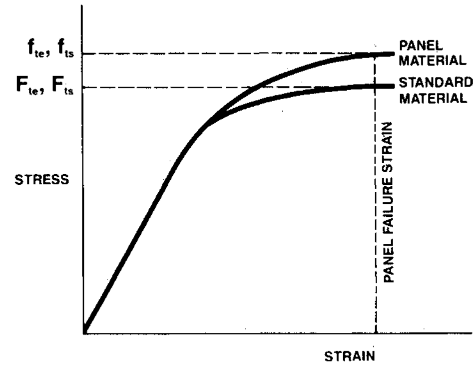

Fig. 2 Reduction of panel strength to standard properties.

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where F_{te} and F_{ts} are the stringer and skin net area allowable stresses at the panel failure strain.

Small fastener specimens with 5% hole-out and made of various aluminum alloys were tested. Load-deflection-to-failure data were obtained for all specimens tested. For conventional 2000 series alloys, with material total strain at fracture of about 15%, the fastener specimen total strain at fracture was about 2.4%, resulting in a total strain concentration of about 6. These specimens had interference fasteners in countersunk holes. The failure strains of the fastener specimens were lower when the fasteners were installed with interference or in cold worked holes. For low ductility alloys, limited test results showed a decrease in the strain concentration factor at failure. To determine the strain concentration factor for a material, it is recommended that a minimum of three coupons and fastener specimens be tested.

Large skin-stringer panels of different alloys were tested to verify the analysis. The strains-to-failure of the panels were consistent with those of the small fastener specimens representing the panel critical elements. The panel load-deflection plot followed the weighted average stress-strain curves for the panel coupons until panel failure was attained. The test failure stresses closely matched the predicted failure stresses for the panels tested.

If large panel tests are conducted to verify the analysis, the following method of reducing the panel data to standard properties is recommended. The correction is made at the panel failure strain as illustrated in Fig. 2.

1) Take representative tensile coupons from the panel skin and stringers. Tensile coupons are taken across the width and length of the skin and from the different legs of the stringers.

2) Average the coupon ultimate tensile strengths for both skin and stringers.

3) Determine the panel gross area failure stress (f_t) by dividing the maximum panel load by the panel gross area.

4) The design gross area panel allowable stress (F_t) is determined by

$$F_t = [(F_{te}A_{en} + F_{ts}A_{sn})/(f_{te}A_{en} + f_{ts}A_{sn})](f_t) \tag{3}$$

where A_{en} is the stringer net area, A_{sn} is the skin net area, and f_{te} and f_{ts} are the average stringer and skin net area stresses, at the panel failure strain, determined from the average coupon stress-strain curves, respectively. F_{te} and F_{ts} are the stringer and skin "standard material" net area stresses, corresponding to the panel failure strain determined from the "standard material stress-strain curves," respectively.

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