RESIDUAL STRENGTH ANALYSES OF SINGLE- AND MULTIPLE-STIFFENED PANELS

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ABSTRACT

This paper presents a residual-strength methodology to predict the failure of single- and multiple-stiffened panels with single- and multiple-through cracks using the critical crack-tip-opening angle (CTOA, Ψ_c) fracture criterion. The critical CTOA value was obtained from tests and analyses of middle-crack tension specimens. To account for high constraint conditions around the crack tip, a "plane-strain" core option was used in the STAGS finite-element shell code analyses. Comparison of measured and predicted load-crack extension and local strain variation for the stiffened panels with either cut or intact stiffeners agreed well. Comparisons made at both the global and local levels indicate that by using two parameters: (1) critical CTOA to control crack extension and (2) a plane-strain core height to define the high-constraint region at the crack front, the residual strength of built-up structures could be accurately predicted (within 5%).

KEYWORDS

Fracture, CTOA, cracks, aluminum alloy, finite element method, plasticity, buckling

INTRODUCTION

Widespread fatigue damage is of concern to the aging commercial transport fleets because the residual strength of a fuselage with a large crack may be significantly reduced by the existence of smaller cracks at adjacent rivet holes, as postulated by Swift [1]. Tests on panels with long lead cracks and multiple-site damage (MSD) have shown that the presence of an array of small adjacent cracks strongly degrades residual strengths [2]. One of the objectives in the NASA Airframe Structural Integrity Program [3] was to develop the methodology to predict failure in damaged fuselage structures in the presence of widespread fatigue damage. The approach was to use a finite-element shell code with global-local, adaptive mesh capabilities and appropriate local fracture criteria to predict progressive failure in complex structures.

Stable crack extension in metallic materials has been studied extensively using elastic-plastic finite-element methods. These analyses were performed to study various fracture criteria. Of these, the crack-tip-opening angle (CTOA) or displacement (CTOD) criterion was shown to be the best suited for modeling stable crack extension and instability during the fracture process. By using high-resolution photographic camera with a video system, Dawicke et al. [4], have shown that the critical angles during stable crack extension in thin-sheet aluminum alloys were nearly constant after a small amount of tearing. Seshadri and Newman [5,6] have also used the finite-element method and the CTOA criterion to predict stable tearing in the presence of severe out-of-plane buckling for several aluminum alloys and a steel. In an effort to develop the methodologies required to predict the residual strength of complex fuselage structures with MSD, a series of tests and analyses have been performed from the coupon level to subscale fuselage simulation tests [6,7]. These series of tests were used to verify the residual-strength methodology based on the critical crack-tip-opening angle (CTOA) failure criterion.

EXPERIMENTS

NASA Langley and the FAA Hughes Technical Center jointly sponsored a series of fracture tests from laboratory specimens to wide stiffened panels with a lead crack and multiple-site damage (MSD) at many adjacent rivet holes [6]. The laboratory specimens and some of the wide panels were tested with anti-buckling guides. Various width compact tension, C(T), and middle-crack tension, M(T), specimens were tested (see Fig. 1). Fracture tests with a single crack, with or without MSD, were conducted with or without anti-buckling guides. A typical MSD crack configuration is shown in Figure 2. MSD crack sizes ranged from 0.25 to 1.3 mm. A series of 305-mm wide M(T) specimens with a central stiffener (intact or cut) was also tested without anti-buckling guides (Fig. 3). Wide panel tests were also conducted on 1016-mm wide panels with five riveted stiffeners (see Fig. 4). The stiffened panels were made of 2024-T3 sheet material (1.6-mm thick) with 7075-T6 stiffeners (2.3-mm thick). The wide panels were allowed to deform out-of-plane and buckle. Measurements were made of load, crack extension, applied end displacement, strain field in the crack-tip region, strains in the intact and broken stiffeners, and displacement fields (local and global).

Large M(T) panels (restrained against buckling) were tested to measure the critical CTOA on the 1.6-mm thick sheet 2024-T3 material during stable tearing and fracture. Two methods were used to measure CTOA: (1) the optical method (OM) [4] and the digital-imaging-correlation (DIC) method [8]. Critical CTOA values are plotted against crack extension in Figure 5. The open and solid symbols show measurements made on opposite sides of the large panels using the OM and DIC method, respectively. After a small amount of crack extension, the critical CTOA values were nearly constant. The average angle was 5.25 degrees (solid line). For small amounts of crack extension, large CTOA values are generally measured on the surface of the specimen, possibly due to severe crack tunneling. The determination of CTOA (5.4 deg., dashed line) that will be used with the STAGS code to predict stable crack extension and fracture will be discussed later.

ANALYSES

The fracture analysis of all laboratory specimens and the wide stiffened panels was made using the STAGS (STructural Analysis of General Shells) code [9] with the critical CTOA fracture criterion. The STAGS code, with the “plane-strain” core option [10], was used in all analyses. Previous analyses of wide, flat panels have shown that the high-constraint conditions around a crack front, like plane strain, have to be modeled in order for the critical CTOA fracture criterion to predict wide panel failures from small laboratory tests [6,7]. The through the thickness deformations around the crack-front region, even in thin-sheet materials, produce a high through the thickness stress, σ_z, which couples with the in-plane stresses, σ_x and σ_y, to greatly elevate the flow stress of the material (increase constraint).

Modeling of Sheet material, MSD, Stiffeners, and Rivets

The critical CTOA (Ψ_c) and the plane-strain core height (h_c) for the thin-sheet 2024 alloy were determined from failure loads on middle-crack tension specimens (no buckling). The fracture constants were then used with STAGS to predict the fracture behavior of C(T) specimens, M(T) specimens that were allowed to buckle, and flat stiffened panels. From previous parametric and convergence studies, it was found that a minimum crack-tip element size of 1-mm (linear-strain element) was sufficient to model stable tearing under elastic-plastic conditions. Crack extension was governed by monitoring the critical CTOA (Ψ_c) at 1-mm behind the crack tip. Rivet connectivity, rivet yielding, stiffener yielding, out-of-plane buckling, and stiffener-sheet contact behavior were modeled during the stable tearing process.

Determination of Critical CTOA and Plane-Strain Core Height

Load-crack-extension results from M(T) specimens (restrained from buckling) were used to determine the critical CTOA and plane-strain core height. Figure 6 shows the failure stress S_f against specimen width. The symbols show test results on specimens with crack-length-to-width ratios of 1/3. Using a critical angle of 5.4 degrees, the failure stresses predicted under plane-stress or plane-strain conditions are shown as the dashed or dash-dot curves, respectively. Neither plane-stress nor plane-strain analyses could capture the experimental trend. To account for high constraint in two-dimensional analyses, a plane-strain core region was defined around the crack tip [10]. The solid curve with the same critical angle and a plane-strain core height of 2 mm, captured the experimental trends very well. There is a small discrepancy between the average value

(5.25 deg.) and CTOA values used in the analyses (5.4 deg.), see Figure 5. There could be numerous reasons for this discrepancy. However, measurements and analyses tend to indicate that the critical CTOA is nearly constant for large amounts of stable tearing and for conditions of extreme plastic deformations.

Comparison of Out-of-plane Displacements

A series of wide panels were tested to demonstrate that the critical CTOA value obtained from laboratory specimens could be used to predict the residual strength of wide panels. A 1016-mm wide panel with a 338-mm crack was tested without anti-buckling guides. Crack extension was monitored at one crack tip and out-of-plane (w) displacements were measured on the other side of the panel using the digital-image correlation system. With increasing applied load, the material along the crack plane, which is under compressive stresses, tend to buckle outwards. A typical comparison between the measurements and the STAGS analyses is shown in Figure 7. The analysis results compare fairly well with the test data all along the crack plane.

FRACTURE ANALYSES OF STIFFENED PANELS

Results from the analyses of the 305- and 1016-mm wide stiffened panels are presented here. The specimens were strain gauged to measure sheet and stiffener strains (and load transfer) as a function of remote load and crack extension. Comparison between the tests and the analyses were made at both global and local levels.

Single Stiffener Specimens

The specimen with a single crack and intact stiffener is shown in Figure 3. Load-crack-extension values measured on a specimen with intact or cut stiffener are shown in Figure 8, as symbols. Because the configuration and loading were symmetric, only a quarter of the sheet and stiffener was analyzed. Results from the STAGS fracture analyses, using the critical CTOA and plane-strain core height, are shown as curves. The predicted results agreed well with the test data. In the analyses, the intact stiffener carried almost 50% of the total load, allowing the specimen with the intact stiffener to carry about 200 kN, and also preventing severe out-of-plane buckling. When the stiffener was cut, the specimen tended to buckle and the load carried by the cut stiffener was dumped near the crack region, causing a severe reduction in failure load.

The load carried by the intact stiffener against the applied load is plotted in Figure 9. The load carried by the stiffener was calculated from the strain-gauge reading. The predicted results (solid curve) agreed well with the measured results until the end of the test. Here the stiffener failed in the test, whereas in the analysis, failure of stiffener was not simulated.

Multiple Stiffened Panel with Single Crack

The specimen configuration and finite-element model for the stiffened panel are shown in Figures 4 and 10, respectively. Because the configuration and loading were symmetric, only a quarter of the sheet and stiffeners was modeled. This model had 13,145 elements, 17,287 nodes, 97,254 degree-of-freedoms (DOF). Figure 11 shows the load-crack extension measurements (circular symbols). The insert shows the relative location of the stiffener. Crack extension was measured until the crack went underneath the stiffener. Once the crack emerged from under the stiffener, the panel failed (open symbols). Whether failure of the panel was due to sheet failure or stiffener failure could not be determined. Failure of either would immediately result in panel failure because the stiffeners were carrying about one-half of the applied load. Two predictions were made using STAGS. First, the panel was restrained against buckling and the predicted results are shown by the dashed curve. The restrained analysis tended to over predict the test data and the predicted failure load was much higher than the test load. However, the unrestrained analysis (buckling allowed) under predicted the early stages of stable tearing but agreed well after about 30 mm of crack extension. The predicted failure load from the fracture of the sheet was 4% higher than the test failure load. The calculated stiffener failure load (x symbol) was extremely close to the actual test failure load. (Stiffener failure load was based on fracture tests conducted on the 305-mm wide specimens with a single intact stiffener at $x = 0$.)

Wide Stiffened Panels with Lead Crack and Multiple-Site Damage

A comparison of the measured and predicted load-against-crack extension for the wide stiffened panel with a lead crack and the 1.3-mm MSD is shown in Figure 12. The insert shows the relative location of the lead crack, open holes, MSD, and the intact stiffener. Open symbols show the test data. The measured load-crack extension values for the data underneath the stiffener were inferred from the load-time trace recorded on this specimen. The solid curve shows the predicted results using the STAGS fracture analysis with the critical CTOA value. Again, the solid symbol denotes the maximum failure load on the panel. After the lead crack linked with the MSD cracks and grew pass the stiffener, the sheet failed when all 24 MSD cracks linked. These results show that MSD at open holes reduce the residual strength by about 30% from that of a panel with only a single crack. The predicted load-crack extension behavior matched the test results very well.

Strain Gauge Measurements and Analyses

In this section, the local strain gauge readings are compared with the analysis results. Each of the wide panel tested had strain gauges mounted on the sheet near the crack-tip region and on either side (front and back) of the stiffeners. On the sheet, strain gauges were placed at three distinct locations as shown in Figure13 around the crack-tip region. The strain gauge readings corresponding to the gauge just above the initial crack tip is shown by square symbols. With an increase in applied load, the strain level builds up monotonically upto a certain point after which it decreases gradually with crack extension. Only the permanent deformation remains in the plastic wake. The strain gauge readings at a location 203-mm ahead of the initial crack tip is shown by circular symbols. At this location, there is a build up of strain with increase in applied load till the crack tip reaches this material point. With further increase in applied load and subsequent crack extension, elastic unloading takes place at this location and only the permanent deformation is left in the wake. Triangular symbols indicate the strain gauge reading corresponding to a location, which is far from the initial crack tip. At this location, the strain value increases with applied load and continues to build with crack extension. Analysis results, represented by the three curves, compared well with the test measurements. Similarly, the strain gauge readings for the first and second intact stiffener compared well with the analyses.

CONCLUDING REMARKS

The STAGS finite-element code and the CTOA fracture criterion were used to predict stable tearing and residual strength of C(T) and M(T) specimens, unstiffened and stiffened wide panels. The measured critical crack-tip-opening angle (CTOA) was nearly constant after a small amount of crack extension for the thin-sheet 2024-T3 aluminum alloy. The STAGS finite element code predicted the out-of-plane deformations quite well. Comparison of measured and predicted loads carried by the intact stiffeners also agreed well. Using the critical CTOA fracture criterion with the plane-strain core option, the STAGS analyses were able to predict stable tearing behavior and residual strength of wide stiffened panels with single cracks and multiple-site damage (MSD) under severe buckling within about 5% of the test loads. Comparisons of local strain variation around the crack-tip region from STAGS analyses compared very well the test data.

REFERENCES

1. Swift, T. (1987) In: *New Materials and Fatigue Resistant Aircraft Design*, pp. 1-77, D. L. Simpson (Ed) EMAS Ltd.
2. McGuire, J. F. and Goranson, U. G. (1992) In: *NASA CP-3160*, pp. 33-48, C. E. Harris (Ed). Washington, D.C.
3. Harris, C. E.; Newman, J. C., Jr.; Piascik, R. and Starnes, J. H., Jr. (1998) *J. Aircraft*. 35 (2), 307-317.
4. Dawicke, D. S.; Sutton, M. A.; Newman, J. C., Jr. and Bigelow, C. A. (1995) In: *ASTM STP 1220*, pp. 358-379, F. Erdogan (Ed). American Society for Testing and Materials, PA.
5. Seshadri, B. R. and Newman, J. C., Jr. (1998) In: *ASTM STP 1332*, pp. 114-134, T. L. Panontin and S. D. Sheppard (Eds). American Society for Testing and Materials, PA.
6. Seshadri, B. R., Newman, J. C., Jr., Dawicke, D. S. and Young, R. D. (1999) In: *NASA/CP-1999-208982*, *Part 2*, pp. 513-524, C. E. Harris (Ed). Washington, D.C.
7. Young, R. D.; Rouse, M.; Ambur, D. R. and Starnes, J. H., Jr. (1999) In: *NASA/CP-1999-208982*, *Part 2*, pp. 408-426, C. E. Harris (Ed). Washington, D.C.
8. Dawicke, D. S. and Sutton, M. A. (1994) Exper. Mech. 34 (4), pp. 357-368.
9. Rankin, C. C.; Brogan, F. A.; Loden, W. A. and Cabiness, H. D. (1997) "STAGS User Manual - Version 2.4," Lockheed Martin Advanced Technology Center, Report LMSC P032594.
10. Newman, J. C., Jr.; Booth, B. C. and Shivakumar, K. N. (1988) In: *ASTM STP 945*, pp. 665-685, D. T. Read and R. P. Reed (Eds). American Society for Testing and Materials, PA.