APPLICATION OF CTOA/CTOD IN THE RESIDUAL STRENGTH ANALYSIS OF BUILT-UP AND INTEGRAL STRUCTURES

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ABSTRACT

Widespread fatigue damage is of great concern to the aging commercial transport fleet because it may lead to loss of structural integrity. Tests on stiffened panels, representative of an aircraft fuselage skin, with long lead cracks and multi-site damage (MSD) have shown that the presence of an array of small adjacent cracks strongly degrades residual strength. This type of damage can also lead to buckling, which considerably reduces the residual strength. As part of the NASA Airframe Structural Integrity Program, a prediction methodology based on critical Crack-Tip-Opening-Angle/Displacement (CTOA/CTOD) was developed to predict the failure of damaged fuselage structures in the presence of widespread fatigue damage. However, the damage tolerance of integrally-stiffened structures must be understood prior to safely introducing this technology into service. NASA Langley Research Center has developed a failure simulation model based on CTOA to predict the strength of integrally-stiffened panels. The methodology was verified by successfully predicting the residual strength of flat, integrally-stiffened panels. Very recently the authors used the same methodology to characterize the residual strength behavior of a curved 7050 integrally-stiffened panel subjected to a combination of constant radial pressure and uniaxial tension loading along the length of the panel. The characterization of this complex test system required further development of the computational toolset. Three-dimensional solid elements along the crack plane were added to accurately capture the geometric non-linear response and the three dimensional constraints around the crack tip region. The authors will discuss the application of solid and shell elements in the analysis and the results of the integrally-stiffened panel test.

1 INTRODUCTION

Widespread fatigue damage is of great significance to the operation of aging commercial transport fleets because the residual strength of a stiffened structure with a single long crack may be significantly reduced by the existence of adjacent smaller cracks as postulated by Swift [1]. Tests on wide structural panels with long-lead cracks and multi-site damage (MSD) have shown that the presence of an array of small adjacent cracks strongly degrades residual strength [2]. This type of damage can also lead to panel buckling, which considerably reduces the residual strength. As part of the NASA Airframe Structural Integrity Program [2], a fracture simulation methodology, based on the critical-crack-tip-opening angle (CTOA),Ψ_c was developed to predict the strength of damaged aircraft structures. Over the years, it has been shown on a number of occasions [3-5] that critical CTOA calibrated from a single test and analysis performed with laboratory compact C(T) or middle cracked tension M(T) specimens accurately predicts the residual strength of wide stiffened panels. The CTOA fracture criterion assumes that stable crack growth occurs when the crack-tip angle reaches a constant critical value. The critical CTOA value appears to be independent of loading, crack length, and in-plane dimensions. However, it is a function of material thickness, material orientation and local crack-front constraint. Modeling the local

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constraint requires either a three-dimensional analysis or a two-dimensional analysis with a plane strain core, h_c, around the crack tip to account for the constraint effects. Of late, the aircraft industry is investigating integrally-stiffened structures with the intention of reducing part count and manufacturing cost [6]. There has been a consistent effort at NASA Langley Research Center to extend the critical CTOA based methodology to the analysis of integrally-stiffened panels. Three different analytical approaches have been applied to model integrally stiffed panels. One analysis approach simulates fracture using two-dimensional shell elements, with a plane strain core at the crack, in a geometrically nonlinear finite element code, STAGS (STructural Analysis of General Shells) [7]. The second analysis approach inherently accounts for constraint effects by using three-dimensional solid finite elements. The third analysis approach retains most of the efficiency of the shell analysis, by modeling the global structure with 2D shell elements and using 3D elements locally at the crack plane to capture the constraint effects. The authors will discuss the application of solid and shell elements in the analysis and the results of the integrally-stiffened panel test.

2 EXPERIMENTS

Previously, wide panel tests were conducted on 1016-mm wide panels with five riveted stiffeners, as shown in Figure 1. These stiffened panels were made of 2024-T3 sheet material (1.6-mm thick) with 7075-T6 stiffeners (2.3-mm thick) [5]. In addition, fracture test on 1220 mm wide curved integrally-stiffened panel made up of 7050 material was conducted at the NASA Langley Research Center (LaRC). The curved integrally-stiffened panel, shown in Fig. 2, was machined from a 38 mm thick plate. Five integral stiffeners of blade and I-cross-sections were located symmetrically across the width of the panel. The curved integrally-stiffened panel had a single lead crack of 178 mm width and was subjected to a combination of constant radial pressure and uniaxial tension loading along the length of the panel. Similarly, a series of 508-mm wide integrally stiffened thick panels with five integral-stiffeners of blade cross section were tested at Alcoa [8]. These panels were made of 2024-T351 and C433-T39 materials. The panel geometry and configuration is depicted in Figure 3.

3 ANALYSIS RESULTS

When modeling the failure of integral structures, care must be taken to ensure the proper fracture properties (CTOA) of the material are used in strength prediction. As a crack grows with stable tearing in a integrally-stiffened panel, the crack tip passes through sections of various thicknesses and orientations, which will have their own critical CTOA. In addition, when the lead crack approaches and severs an intact integral stiffener, crack branching occurs. When crack branching occurs the crack growth at multiple crack tips is controlled with different values of CTOA. This is shown schematically in Figure 4.

3.1 Fracture Analyses of Riveted Stiffened Panels

The specimen configuration and a typical finite-element model for the stiffened panels are shown in Figures 1 and 5, respectively. This model contained 13,145 shell elements and 17,287 nodes. For brevity, only two of wide stiffened panel analyses results are discussed. For more information on prediction methodology followed, refer to References 4 and 5.

3.1.1 Multiple Stiffened Wide Panel with a Single Lead Crack

Figure 6 shows the test measurements (symbols) of load versus crack extension made on the panel with a single crack. The insert shows the relative location of the stiffener. Circular symbols show the results for multiple stiffened wide panel the a single lead crack. The large gap in the data was when the crack was underneath the stiffener. Once the crack emerged from under the stiffener, the panel failed (solid symbol). 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 analysis assumed the panel was restrained against buckling and the predicted results are shown by the dashed curve in Figure 6. After 20 mm of crack extension the restrained analysis tended to significantly over predict the test data and the predicted failure load was much higher than the test failure 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

3.1.2 Wide Stiffened Panel with a 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 7. The insert shows the relative location of the lead crack, open holes, MSD, and the intact stiffener. Diamond symbols show the test data. The vertical steps in the data (with no crack extension) occurs when the crack linked with an open hole, and additional load was required to fracture the material at edge of the hole. Again, the solid symbol denotes the maximum failure load on the panel. After the lead crack linked with the MSD cracks and grew past the stiffener, the sheet failed with all 24 MSD cracks linking. Complete panel failure then occurred at about a 10% higher load, to break the stiffeners. These results show that MSD at open holes reduced 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.

3.2 Fracture Analysis of a Curved Integrally Stiffened Panel

The fracture analysis of a curved integrally-stiffened panel was carried out using STAGS code. The quadrilateral shell element was under ‘plane-stress’ conditions everywhere in the model except for a ‘core’ of elements along the crack plane that were under ‘plane strain’ conditions [4]. Elastic-plastic material behavior of the sheet and integral stiffener were approximated by multi-linear stress-strain curves. The analysis methodology and the calibration procedure adopted in the determination of fracture parameters are discussed in references 9 and 10. The remote loading was a combination of constant radial pressure and uniaxial tension loading along the length of the panel. Figure 8 shows the test measurements (open symbols) and analytical prediction (solid line). The insert shows the relative location of the intact integral stiffener close to the crack tip. Figure 8 shows that failure occurred when the crack tip reached the edge of the integral stiffener (solid symbol). The analysis predicted similar behavior; the crack growth became unstable when the crack tip entered the integral stiffener. The load-crack extension data from the analysis compared well with the test measurements and the failure load predicted from the STAGS analysis was within 3% of test failure load.

3.3 Fracture analyses of a 508-mm wide integrally-stiffened thick panel

The Alcoa 508-mm wide integrally stiffened thick panels were analyzed using both ZIP3D [11] and the STAGS codes. ZIP3D is an elastic-plastic material non-linear finite element software with capabilities to carry out fatigue and fracture analysis. Figures 3 and 9 show the integrally stiffened thick panel configuration and a typical finite-element model of the panel used in the analysis. Figure 9 shows the local mesh pattern used near the crack in three dimensional ZIP3D analysis. The remote loading was applied as uniform displacement. The 508-mm wide integrally-stiffened thick panels were also analyzed with solid and shell elements by using STAGS finite element software. The rigid links were used to maintain displacement compatibility across the solid and shell element transition region. Comparison of load-crack extension results for a panel made from 2024-T351 is shown in Figure 10. As experimental load-crack extension data was not available for comparison, only maximum load is indicated by horizontal dashed line. Solid, dash-dot-dot and dash-dot lines indicate the ZIP3D, STAGS and STAGS3D analyses results respectively. The insert shows the location of the intact integral stiffener. ZIP3D, STAGS and STAGS3D analysis results compare well with the experimental maximum and are within 2% of the test maximum load. All the analyses have similar characteristics and once the lead crack passes the integral stiffener, the crack growth becomes unstable.

4 SUMMARY

STAGS analysis was able to predict within 5% of the measured stable tearing behavior and residual strength of wide riveted stiffened panels with single cracks and MSD under severe buckling. The residual strength prediction of a 1220-mm wide curved integrally stiffened panel was within 3% of the test failure load. ZIP3D, STAGS and STAGS3D residual strength prediction of 508-mm wide integrally stiffened Alcoa thick panel compared well and were within 2% of experimental maximum loads. By using solid and shell elements in STAGS analysis, plane-strain core height calibration can be totally eliminated and only critical CTOA is required in residual strength prediction. These studies have demonstrated that both STAGS and ZIP3D have all the capability and features that are required in the analysis of both thin and thick integrally stiffened panels. With the success in the fracture analyses of cracked built-up and integrally-stiffened panels, the finite-element software and CTOA fracture criterion is useful in the fracture design of integrally-stiffened thin and thick structures.

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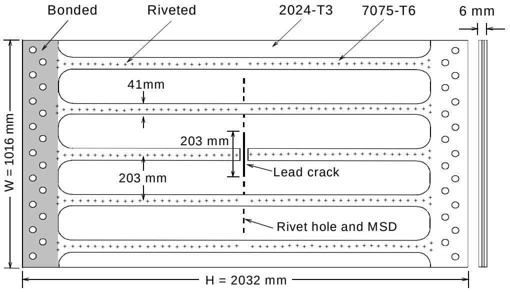

Fig. 1. Wide stiffened panel with single lead crack and MSD.

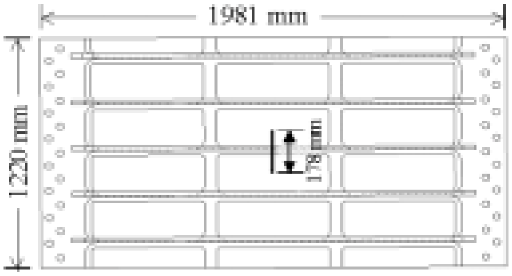

Fig 2. 1220 mm wide curved integrally-stiffened wide panel with a single lead crack.

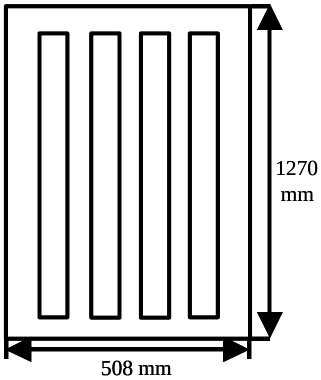

Fig.3 A typical 508-mm wide integrally-stiffened thick (Alcoa) panel.

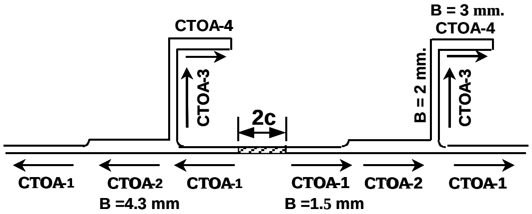

Fig. 4. Schematic representation of crack branching with CTOA criterion.

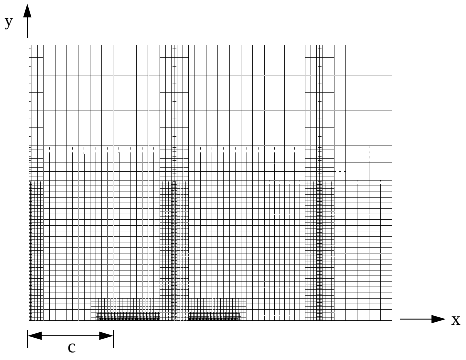

Fig. 5. Typical finite-element model of stiffened 1016 mm wide specimen.

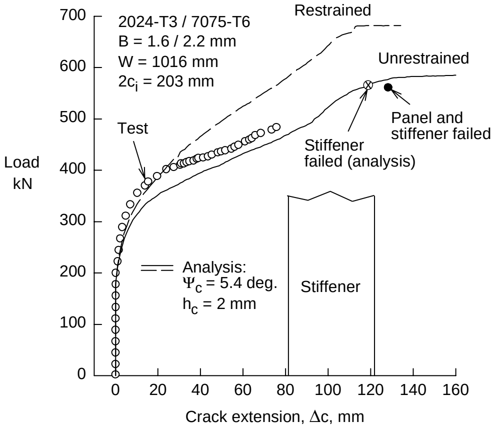

Fig. 6. Applied load against crack extension for stiffened panel with single crack.

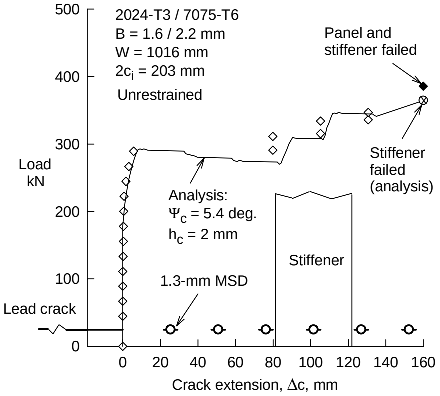

Fig. 7. Applied load against crack extension for stiffened panel with crack and 1.3 mm MSD.

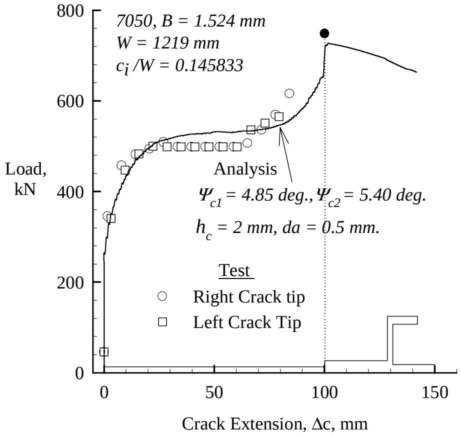

Fig. 8. Load against crack extension results for 1220-mm wide curved integrally-stiffened panel.

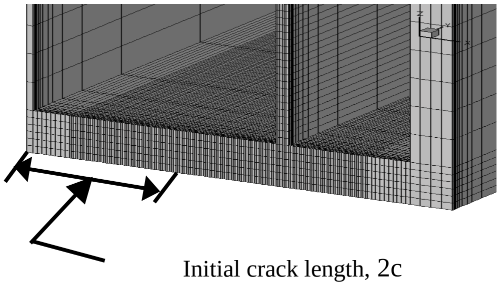

Figure 9. Typical finite element model of an integrally-stiffened thick panel.

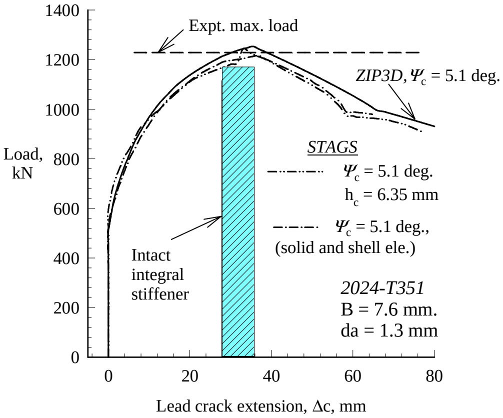

Fig. 10. Comparison of crack extension data for 508-mm wide integrally-stiffened panel.