ANALYSIS OF THE RESIDUAL STRENGTH AND LINK-UP STRESS OF ALUMINIUM PLATES WITH MULTI-SITE DAMAGE

G. D. Ciliato & S. H. S. Carneiro
Institute of Aeronautics and Space
Aerospace Technical Center - CTA / IAE / ASA, Brazil

ABSTRACT

This work presents two methods for the estimation of the link-up stress and residual strength of structural elements with multi-site damage - MSD. The subject of MSD in aeronautical structures was brought into attention to the scientific community after the Aloha Airlines Boeing 737 accident in 1988 and it is currently a topic of numerous investigations, sponsored by aeronautical companies and airworthiness authorities.

The first method is known in the literature as the link-up method. Its basic hypothesis states that two neighboring cracks merge when the two correspondent plastic zones touch each other. The method is very intuitive and has gained popularity due to its simplicity and reasonable accuracy for preliminary design.

The second method is more suitable to structural components of ductile material, which present significant amounts of plastic deformation prior to failure. Typical examples of such structures are aircraft fuselage skins, usually made of ductile aluminum alloys. The method is based on the crack tip opening angle, CTOA. This elastoplastic fracture mechanics concept was originally introduced in 1963, and has gained popularity in MSD research since the early 1990's. In recent years, the CTOA-based method has been selected by NASA as the best approach for the fracture mechanics evaluation of structural elements of an International Space Station module.

The two methods are applied to the investigation of MSD in different stiffened panels. The results obtained with both methods are compared to experimental data found in the literature. The comparisons show that the CTOA approach presents excellent correlation with experimental data for all the studied examples. The same configurations, but without MSD cracks, are analyzed with the CTOA approach to capture the MSD effect on the link-up tension.

1 INTRODUCTION

On April 28, 1988, when the aeronautical community believed that the damage tolerance design philosophy was able to ensure aircraft structural integrity, the Aloha Airlines Boeing 737 suffered an in-flight structural failure. The failure resulted from the link-up of small fatigue cracks extending from adjacent rivet holes in a fuselage lap-splice joint. The accident motivated the beginning of intense research efforts in the field of Fracture Mechanics, towards the understanding of a new phenomenon: MSD.

The simultaneous presence of cracks in the same structural element is usually referred to as Multiple Site Damage - MSD (Swift [1]). The simultaneous presence of cracks at multiple structural details that are of sufficient size and density to affect damage tolerance requirements is known as Widespread Fatigue Damage – WFD (Swift [1]).

There are many different methods to predict the fracture behavior and residual strength of aircraft fuselage structures subjected to WFD (Nestenko [2], Chen [3], Collins [4], and Duong [5], for example). However, a fracture criterion is required which is independent of the geometry of the structure, the crack length, the presence of MSD, and which has a reliable correlation with experiments. Thin sheet metallic structures generally undergo stable crack growth before the occurrence of fast fracture and, in these cases, Small Scale Yielding - SSY conditions are no longer valid. In order to characterize elastic-plastic crack growth in thin-sheet metals, the Crack Tip Opening Angle - CTOA is a very useful parameter (Chen [3]). Due to its success in modeling ductile failures, the CTOA criterion has become the method recommended by many researchers in the field of Fracture Mechanics (Ma [6], Newman [7], Starnes [8], Seshadri [9], Hampton [10], and Salvini [11].

A much simpler approach, called the link-up model or the plastic zone touch model (Swift [1]), is also presented and discussed in this article. This method was one of the first to appear in the literature and is often cited as very useful in preliminary design stages due to its simplicity and geometric appeal.

1.1 Link-up criterion

The fracture strength of most aluminum alloys is limited to the typical net section yield strength (Swift [1]). Therefore, it appears reasonable to assume that link-up of a lead crack and the MSD crack would occur when the intact ligament stress between them reaches the yield strength of the material. The lead crack plastic zone size and the MSD crack plastic zone can be calculated using Irwin plastic zone model. As the remote stress level increases, the plastic zone sizes will increase until they touch each other, and this is the instant when the link-up will occur (Swift [1]). In this article the plastic zone sizes are calculated using the Irwin model, using values for the stress intensity factor determined by the finite element method.

1.2 CTOA criterion

Guidelines for using the CTOA criterion to predict fracture behavior and residual strength of built-up aircraft fuselages are presented in Chen [3] and are implemented here. The 2D finite element analyses are conducted using FRANC2D/L software. The discrepancy between 2D analyses and test results is related to the 3D constraint effect. Although thin-sheet structures behave essentially in plane stress, the conditions local to the crack tip approach a state of plane strain (Chen [3]). In 1988, Newman et al. [7] showed that, by defining a core of plane strain elements above and below the crack path, while all other elements in the model are assigned as plane stress, they were able to obtain very accurate numerical simulations. This approach is usually referred to as the "plane-strain core" approach.

Analyses based on the CTOA fracture criterion are direct simulations of realistic crack growth, so multiple crack growth interaction, link-up of cracks and residual strength of the structure are automatically captured as the crack propagates (Chen [3]). In Figure 1, graphic (a), it is represented the results for tests under displacement control. This may illustrate a test of a CT, MT or even a MSD specimen when the link-up load of the cracks and the residual strength are reached together. On graphic (b), it can be noticed the occurrence of link-up of cracks in a lower stress level, whereas the upper stress level represents the failure of the MSD specimen.

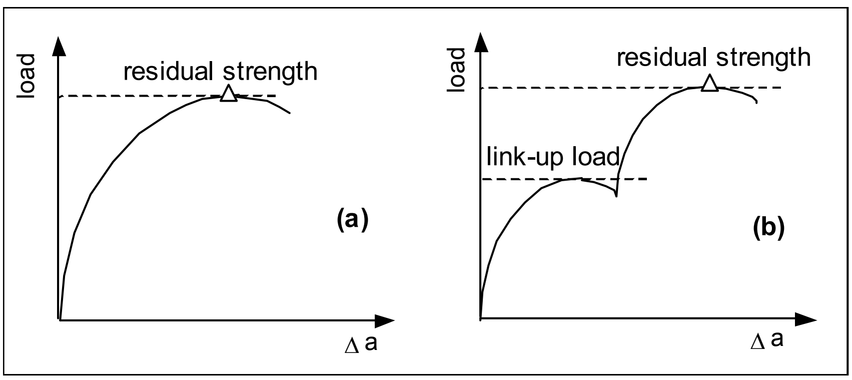

Figure 1: Residual Strength of specimen under displacement control (Chen [3]).

2 RESULTS

2.1 Numerical Analyses of Panels with MSD

The CTOA fracture criterion is used to predict link-up tension in stiffened panels with a lead crack and MSD cracks. There are 12 different MSD configurations of single-bay panels and 8 different MSD configurations of two-bay panels with severed central stiffeners. Figure 2 shows these configurations.

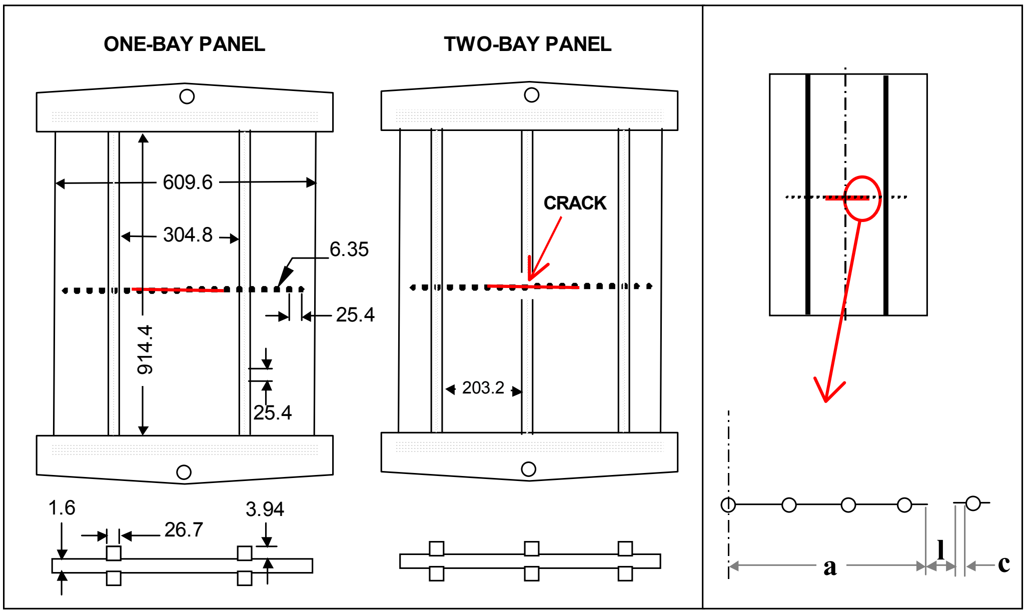

Figure 2: Single-Bay and Two-Bay stiffened panels (mm) (Smith [12]).

Figure 2 shows the panels tested at Wichita State University (Smith [12]). These 20 configurations had man-made lead crack and MSD cracks produced by electro-discharge-machine (EDM). The MSD cracks emerge from both sides of open holes adjacent to the lead crack. The stiffeners were on both sides of the panel and mid-span fixtures were used to prevent buckling along the crack line. The material of the stiffeners was assumed to be the same of the plates: 2024-T3, and its properties are taken from MIL-HDBK-5H.

Starnes [8], reports the use of a critical CTOA value of 5.4º and a plane-strain core height of 0.08in (2mm). Due to the fact that all the dimensions of the lead and MSD cracks are multiple of the length 0.025in, it was convenient to use this value as the length of the side of the elements in the crack path. It was necessary to change the "measuring point" for the CTOA, from the standard 0.04in behind the crack tip to 0.05in behind the crack tip, which is equivalent to twice the element length. Considering that the CTOA profile is constant during stable tearing, it was determined the value of CTOA measured at 0.05in from the crack tip when the critical CTOA is reached at 0.04in from the crack tip. Figure 3 shows the crack opening profile used to change the point of CTOA reading.

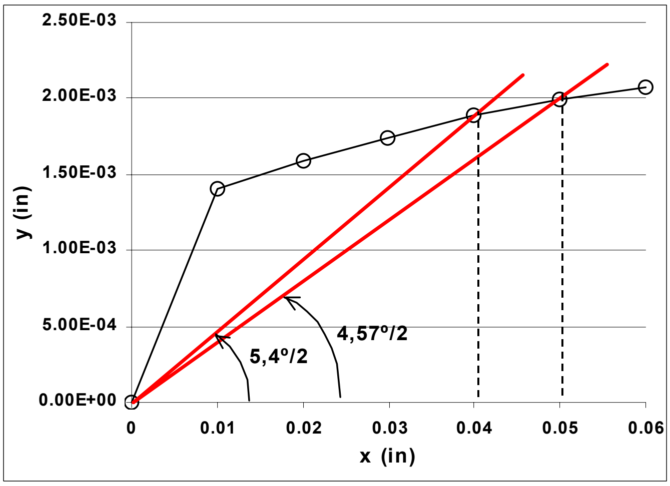

Figure 3: The crack opening profile and the change in the CTOA reading point.

When the critical CTOA value of 5.4º is reached 0.04in behind the crack tip, the CTOA value that is read at 0.05in behind the crack tip is 4.57º. Therefore, the associated crack tip opening displacement is 0.00399in. This was the value used in the FRANC2D/L analyses.

A comparison between the results of the analyses with the CTOA criterion and with the plastic zone touch model are shown in Figure 4.

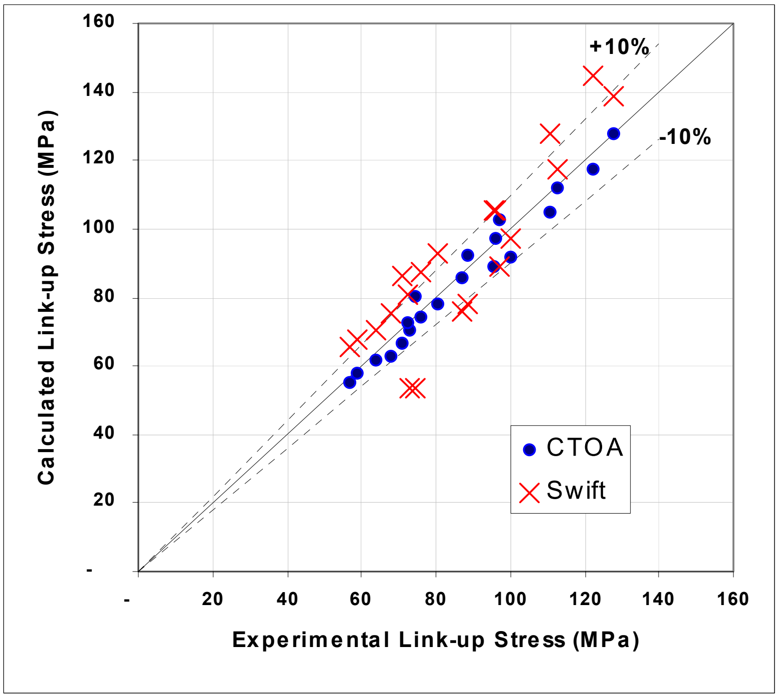

Figure 4: CTOA fracture criterion and plastic zone touch model criterion analyses.

From Fig. 4, it can be noticed that the CTOA method leads to better results for MSD specimens of thin aluminum sheets in all cases investigated. It can also be inferred that the Swift model gives more conservative results for the configurations where a greater amount of stable tearing occurs. Even though the results from Swift's method are less accurate, its simplicity makes it attractive for preliminary analyses.

2.2 MSD cracks effect on link-up tension

The same panels configurations, but without MSD cracks, are analyzed to show the MSD effect in the values of the link-up tension. Now the remote load is increased until the lead crack reaches the closest hole. The results of theses analyses are shown in Table 1. The results show that even a tiny MSD crack emerging 0.05in from the adjacent hole (configurations 1-3, 6-9 e 12) is able to decrease the link-up tension in more than 30%.

Table 1: MSD cracks effect in the link-up tension.

		Dimension (mm)			Without MSD	With MSD	Decrease
	Configuration	**a**	**c**	**l**	**(MPa)**	**(MPa)**	**(%)**
ONE BAY	**1**	118.7	1.3	3.8	**112.2**	**70.5**	**37.2**
	2	116.2	1.3	6.4	**135.5**	**85.7**	**36.8**
	3	113.7	1.3	8.9	**156.8**	**91.5**	**41.6**
	4	108.6	3.8	11.4	**184.2**	**88.9**	**51.8**
	5	107.3	2.5	14.0	**188.1**	**104.7**	**44.3**
	6	106.0	1.3	16.5	**191.9**	**117.5**	**38.8**
	7	144.1	1.3	3.8	**135.8**	**80.5**	**40.8**
	8	141.6	1.3	6.4	**159.4**	**92.4**	**42.0**
	9	139.1	1.3	8.9	**171.5**	**102.6**	**40.1**
	10	134.0	3.8	11.4	**187.4**	**97.3**	**48.1**
	11	132.7	2.5	14.0	**188.7**	**111.9**	**40.7**
	12	131.4	1.3	16.5	**191.9**	**127.8**	**33.4**
TWO BAY	**13**	107.3	2.5	14.0	**122.4**	**78.4**	**36.0**
	14	108.6	3.8	11.4	**118.6**	**66.6**	**43.8**
	15	109.9	5.1	8.9	**114.8**	**58.2**	**49.3**
	16	132.7	2.5	14.0	**119.2**	**74.3**	**37.7**
	17	134.0	3.8	11.4	**114.1**	**62.6**	**45.2**
	18	135.3	5.1	8.9	**110.3**	**55.2**	**50.0**
	19	158.1	2.5	14.0	**118.6**	**72.6**	**38.8**
	20	159.4	3.8	11.4	**116.7**	**61.6**	**47.2**

3 CONCLUSIONS

In ductile materials used in aircraft fuselages, stable crack growth before fast fracture and failure is likely to occur. Under such circumstances, linear elastic fracture mechanics is not able to characterize the fracture behavior of the structure. Since crack growth is no longer under small-scale yielding conditions, elastic-plastic fracture mechanics is necessary. The CTOA fracture criterion, that states that the crack opening profile during stable tearing is constant, leads to excellent results. The available computer resources based on the finite element method have rendered the CTOA criterion even more attractive for practical applications. The application of the

CTOA criterion requires finite element codes with elastic-plastic capabilities, in order to capture the effect of plastic deformations at crack tip, and to keep track of the load history.

In the plastic zone touch model, introduced by Swift, the link-up of the lead crack with the MSD crack occurs when their plastic zones touch each other. In this case there is no stable crack growth before the link-up stress is reached. Its application to thin panels of ductile materials is restricted and leads to very conservative results in some cases.

The necessity of using solid elements to model thin plates, in order to capture the three-dimensional stress state close to the crack tip, was avoided in this work. An alternative option was adopted, which is based on a plane-strain core of elements along the crack path, whereas the other elements are in plane-stress state.

4 REFERENCES

[1] T. Swift. Widespread fatigue damage monitoring - issues and concerns. In Proceedings from 5th International Conference on Structural
Airworthiness of New and Aging Aircraft, pages 133-150, June 1993.

[2] G. I. Nesterenko and B. G. Nesterenko. Residual strength analysis of the stiffened structures with WFD, MSD and single crack. In 6th Joint FAA/DoD/NASA Conference on Aging Aircraft, San Francisco, CA, USA, September 2002.

[3] C. Chen, P. A. Wawrzynek, and A. R. Ingraffea. Crack growth simulation and residual strength prediction in airplane fuselages. Technical Report NASA CR-1999-209115, NASA Langley Research Center, Hampton, Va. 23365, March 1999.

[4] R. A. Collins, D. J. Cartwright, and P. J. Gregson. A direct complex stress function approach for modeling stiffened panels containing multiple site damage. Theoretical and Applied Fracture Mechanics, 31:105-117, 1999.

[5] C. N. Duong, C. C. Chen, and J. Yu. An energy approach to the link-up of multiple cracks in thin aluminum alloy sheets. Theoretical and Applied Fracture Mechanics, 35:111-127, 2001.

[6] L. Ma, P. W. Lam, M. T. Kokaly, and A. S. Kobayashi. CTOA of a stable crack in a thin aluminum fracture specimen. Engineering Fracture Mechanics, 70:427-442, 2003.

[7] Jr. Newman, J. C., C. E. Harris, R. S. Piascik, and D. S. Dawicke. Methodology for predicting the onset of widespread fatigue damage in
lap-splice joints. Technical Report NASA TM 1998 208975, NASA Langley Research Center, Hampton, Va. 23365, December 1998.

[8] J. H. Starnes, J. C. Newman, C. E. Harris, R. D. Young, C. A. Rose, and M. A. James. Advances in residual strength analysis from laboratory coupons to structural components. In ICAF, 2001.

[9] B. R. Seshadri, Jr. Newman, J. C., and D. S. Dawicke. Residual strength analyses of stiffened and unstiffened panels - part
II: Wide panels. Engineering Fracture Mechanics, 70:509-524, 2003.

[10] R. W. Hampton and D. Nelson. Stable crack growth and instability prediction in thin plates and cylinders. Engineering Fracture Mechanics, 70:469-491, 2003.

[11] P. Salvini, A. Fonzo, and G. Mannucci. Identification of CTOA and fracture process parameters by drop weight test and finite element simulation. Engineering Fracture Mechanics, 70:553-566, 2003.

[12] B. L. Smith, A. L. Hijazi, A. K. M. Haque, and R. Y. Myose. Modified linkup models for determining the strength of stiffened panels with multiple site damage.