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A BRIEF HISTORY ABOUT MULTIPLE SITE DAMAGE (MSD) AND CURRENT AVAILABLE METHODOLOGIES TO PREDICT ITS EFFECT IN REAL AIRCRAFT FUSELAGE STRUCTURES[1]

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Abstract

Since the accident with an Aloha Airliners Boeing 737 in 1988, the study of Multiple Site Damage (MSD) has became one of the most important topics of research in the field of aging aircraft by regulatory agencies and by aerospace industry in general. MSD is becoming even more relevant as long as many airlines, pushed by continuous reductions in the average flying fares, are increasingly investing in extension of aircraft lives for their fleets. The present work has as a main objective to present an overview of the MSD phenomenon and to outline the current available methodologies to estimate the MSD effect in real aircraft fuselage structures based on already developed models by regulator and academies. Different methods to predict residual strength of structural elements with multiple cracks will be discussed. A brief discussion about the simplest and preliminary verification using Link-Up model is presented and more detailed and recent methodologies based on Crack Tip Opening Angle (CTOA) are discussed in some detail. In order to verify the methodologies acceptance and limitations, a comparison between analytical results and experimental data provided in the literature for standard specimens is performed.

The authors will also discuss the future works and next steps to be developed in order to define the implementation of standard procedures which take in to account the MSD effect during the aircraft development.

Keywords: Multiple site fatigue damage; Damage tolerance; Aircraft structural analysis.

UMA BREVE HISTÓRIA SOBRE DANO POR MÚLTIPLAS TRINCAS (MSD) E AS ATUAIS METODOLOGIAS DISPONÍVEIS PARA PREDIÇÃO DO SEU EFEITO EM ESTRUTURAS AERONÁUTICAS

Resumo

Desde o acidente com um Boeing 737 da Aloha Airlines em 1988 o estudo de danos múltiplos (MSD) tornou-se um dos temas mais importantes da pesquisa do campo do envelhecimento de aeronaves pelos órgãos certificadores e pela indústria aeronáutica em geral. O problema de MSD está se tornando ainda mais relevante uma vez que muitas companhias aéreas, impulsionadas por reduções contínuas na tarifa média dos vôos, estão cada vez mais investindo na extensão da vida de aeronaves para suas frotas. O presente trabalho tem como objetivo apresentar uma visão geral do fenômeno do MSD e para definir as metodologias atualmente disponíveis para estimativa do efeito do MSD nas estruturas das fuselagens de aeronaves com base em modelos já desenvolvidos pelos órgãos certificadores e academia. Diferentes métodos de predição da resistência residual de elementos estruturais com múltiplas trincas serão discutidos. Uma breve discussão sobre os métodos mais simples e verificação preliminar usando o modelo de Link-Up será apresentada, e metodologias recentes baseadas no Crack Tip Opening Angle (CTOA) serão discutidos em detalhe. A fim se de verificar a aceitação de metodologias e suas limitações, a comparação entre os resultados analíticos e os dados experimentais fornecidos na literatura para amostras padrão será apresentada. Os autores discutem também os trabalhos futuros e os próximos passos a serem desenvolvidos a fim de definir a aplicação dos procedimentos padronizados que consideram o efeito do MSD durante o desenvolvimento da uma aeronave.

Palavras-chave: Dano por múltiplas trincas; Tolerância ao dano; Análise estrutural em aeronaves.

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1 INTRODUCTION

The Multiple Site Damage (MSD) became worldwide known after the accident with and old Boeing 737-200 operated by Aloha Airliners. On April 28, 1988 the B737-200, N73711 was scheduled to perform the flight 243 from Hilo to Honolulu. At 13:25 PM the aircraft take-off from Hilo Airport and climbed to 24.000fts (FL240). After stabilized at cruise level, an explosive decompression suddenly occurred. The damage consisted of total separation and loss of a major portion of upper fuselage skin, from station 368 to station 540 (about 18 feet) as shown below.

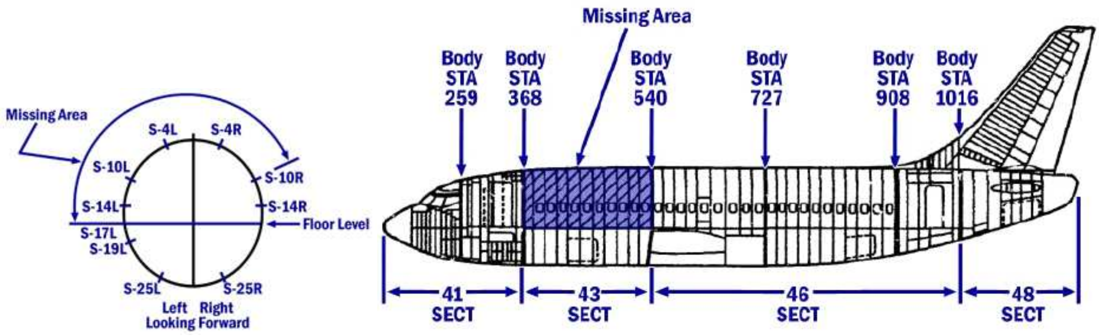

Figure 1. B737-200 body stations and damage extension.(1)

After decompression, the first officer declared emergency and few minutes later he safely landed the aircraft at Maui Airport. There were eight serious injuries and one fatality (a flight attended that was not using her seat belt at the moment of decompression). After landing a passenger that was attending the flight 243, reported the crew that when she boarded the aircraft, she had seen a longitudinal fuselage crack, but she didn't report before takeoff. The longitudinal fuselage crack was not detected by first officer of the day during walk around inspection. The National Transport Safety Board (NTSB) considered that the failure of the Aloha Airlines maintenance program to detect the presence of significant disbonding and fatigue damage was the major cause that contributes to the accident.
The aircraft had been manufactured in 1969 and had since accumulated 89680 flight cycles and 35496 flight hours at the time of accident, the second highest number of cycles in the worldwide B-737 fleet.(1)

Figure 2. Aloha Airliners B737-200 after landing at Maui Airport.(1)

Investigations indicated the large loss of pressurized fuselage skin was caused by rapid link-up of many fatigue cracks in the same longitudinal skin splice. The original skin-splice configuration consisted of cold bonded structure, using an epoxy-impregnated woven cloth and three rows of countersunk rivets. This configuration showed to be not effective in terms of environmental durability, according to Boeing

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service history of B-737. The difficulties found during bonding process, resulted in random appearances of bonds with low environment strength with susceptibility to corrosion. The combination of high number of inter island flights, aggressive environment where Aloha Airlines routes were operated, inefficient cold bonding that allowed moisture to enter the skin splice during service leads to fatigue cracks initiated from rivet holes due to knife effect and linked up rapidly until the separation of major portion of forward fuselage upper skin structure.(2)

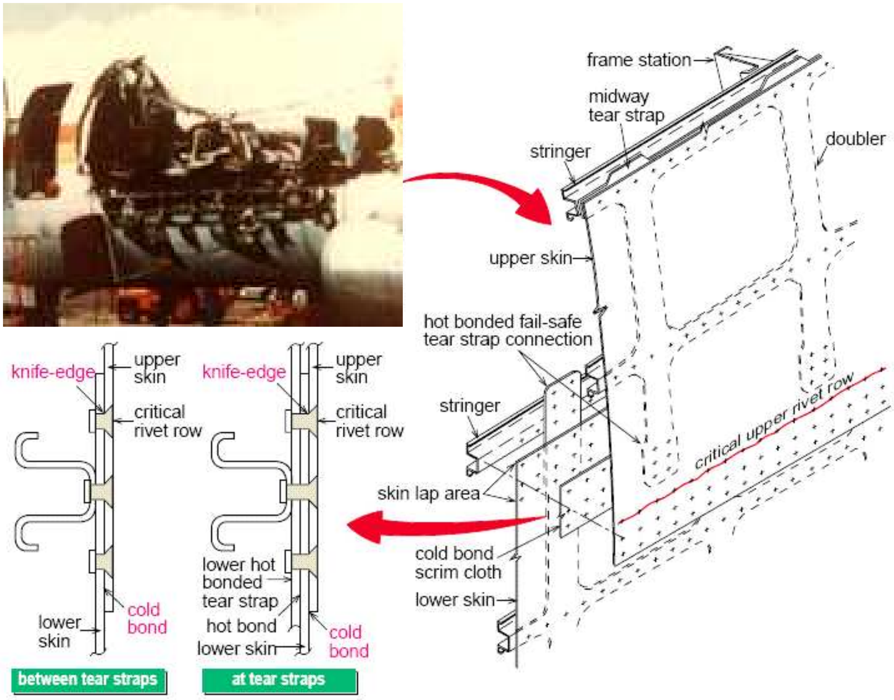

Figure 3. Structural aspects of the Aloha Airliners B737-200 accident.(2)

All the factors described above associated with the failure of Aloha Airlines maintenance program to detect the presence of significant disbonding and fatigue damage contributes significantly to the accident. The accident of Aloha Airliners flight 243 brings a series of safety recommendations as well as procedures to be evaluated and applied by aircraft industry, regulatory agencies and operators to guarantee the continued airworthiness of aging aircraft fleet. The major recommendations and actions generated by NTSB investigation(1) are listed below:
provide specific guidance and engineering support to the Principal Maintenance Inspectors to evaluate modifications of airliner maintenance programs;

- full scale fatigue testing to a minimum of two times the projected economic service life. It must be demonstrated by test evidences that the aircraft structure will not be susceptible to catastrophic failure due to widespread fatigue damage (WFD) within the design service goal of airplane, according to 25.571c paragraph b;(3)
- as a result of full scale fatigue testing and subsequent inspections, the aircraft manufactures should identify structures prone to MSD occurrence and adopt inspections programs for the detection of such damage.

As a preventive action in order to avoid another structural failure similar to the explosive decompression and fuselage skin separation of a high cycled Aloha Airlines B-737, Boeing Commercial Aircraft performed an extensive structural work program estimated in a quarter billion dollars on about 900 B-737´s. Those repairs also affected some 1300 additional 737´s outside of USA. The FAA recognized that the lap joint modification specified in this proposed Airworthiness Directive (AD) would involve many labor hours, complex maintenance actions, like as removing interior components, modification of certain lap joints and consequently long time of aircraft out-off service. The labor cost estimated was U$$ 100.000 for each airplane, according to Aviation Maintenance Magazine.(4)

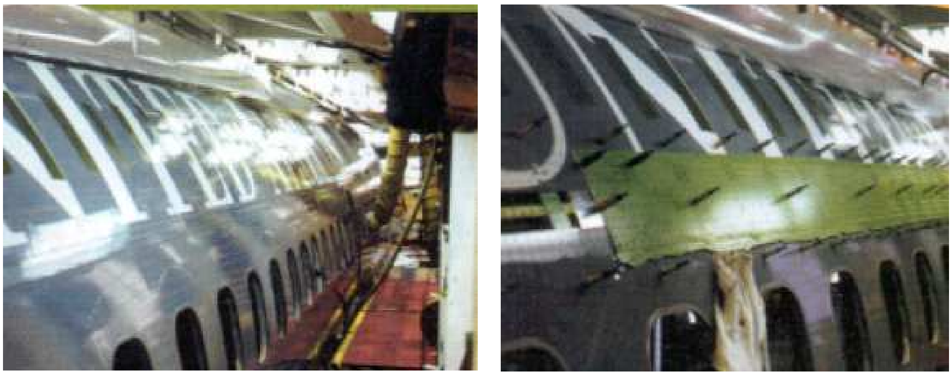

Figure 4. Service bulletin campaign applied to B-737 fleet including doubler installation on stringer 10L from station 360 to 540 above window line.(4)

The main purpose of this article is to outline the current available methodologies to predict the MSD effect in real aircraft fuselage structures. First a description of typical areas prone to MSD failure will be presented. Then, an overview of the methodologies that have been developed to predict the MSD will be outlined, as well as methods for simulation of multiple crack growth and verification of residual strength reduction due to MSD occurrence. Finally the authors discuss the future trends and impacts for aircraft manufactures and operators to comply with new requirements to ensure the continued airworthiness of aging aircraft.

For purposes of allowing a better understanding the foregoing discussion, some important definitions are described here according to Damage Tolerance and Fatigue Evaluation of Structure:(5)

Widespread Fatigue Damage (WDF) in a structure is characterized by the simultaneous presence of cracks at multiple structural details that are of sufficient size and density whereby the structure will no longer meet its damage tolerance requirement (i.e. to maintain its required residual strength after partial structural failure).

Multiple Site Damage (MSD) is a source of widespread fatigue damage characterized by the simultaneous presence of fatigue cracks in the same structural element (i.e. fatigue cracks that may coalesce with or without other damage leading to a loss of required residual strength).

Multiple Element Damage (MED) is a source of widespread fatigue damage characterized by simultaneous presence of fatigue cracks in similar adjacent structural elements.

After the Aloha accident many international working groups had been organized to improve safety and solve the aging airplane problems, namely the Airworthiness Assurance Working Group (AAWG). In 1983 the AAWG issued a final report recommending the WFD evaluation of 11 aging aircraft models. The airplane models are, B707, B727, B737C, B747C, DC8, DC9, DC10, L1011, A300, F28, BAC1-11.

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2 AIRCRAFT AREAS PRONE TO MSD FAILURE OCCURRENCE

The Industry Committee on Widespread Fatigue Damage presented in 1993 a report describing the list of aircraft prone areas and structures potentially susceptible to MSD/MED occurrence.(6) According to the definitions presented in that document, the susceptible structures are defined as structures that have the characteristics of similar structural details operating at uniform stress levels where structural capability could be significantly degraded by the presence of multiple cracks. The susceptible areas for MSD/MED occurrence in a typical commercial aircraft structure are presented in Figure 5.

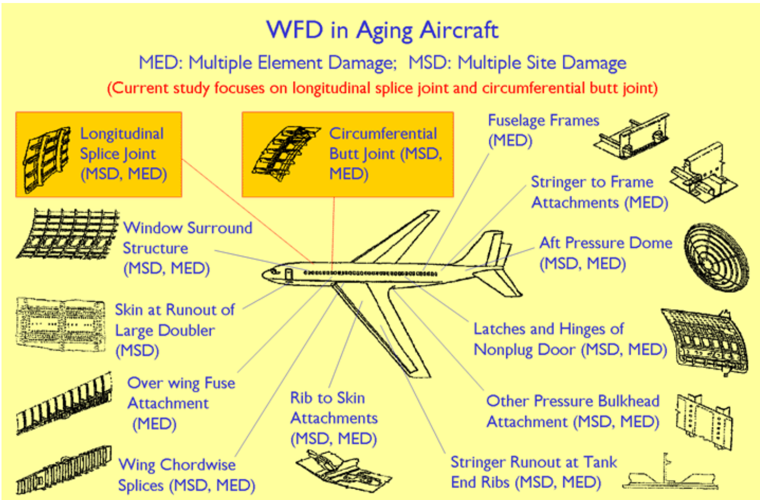

Figure 5. Susceptible structures and prone areas to MSD/MED occurrence[7].

3 OVERVIEW OF CURRENT MSD METHODOLOGIES

3.1 Residual Strength Analysis

This evaluation consists of verifying the presence of MSD adjacent to a lead crack, and its influence in terms of residual strength reduction. According to Figure 6, the capacity to withstand the design loads can be drastically reduced due to MSD effect, compared with intact structure. For the MSD scenario it is also possible to verify the increasing crack growth compared with single crack, as well as reduction in the crack growth period between detectable and critical crack size.

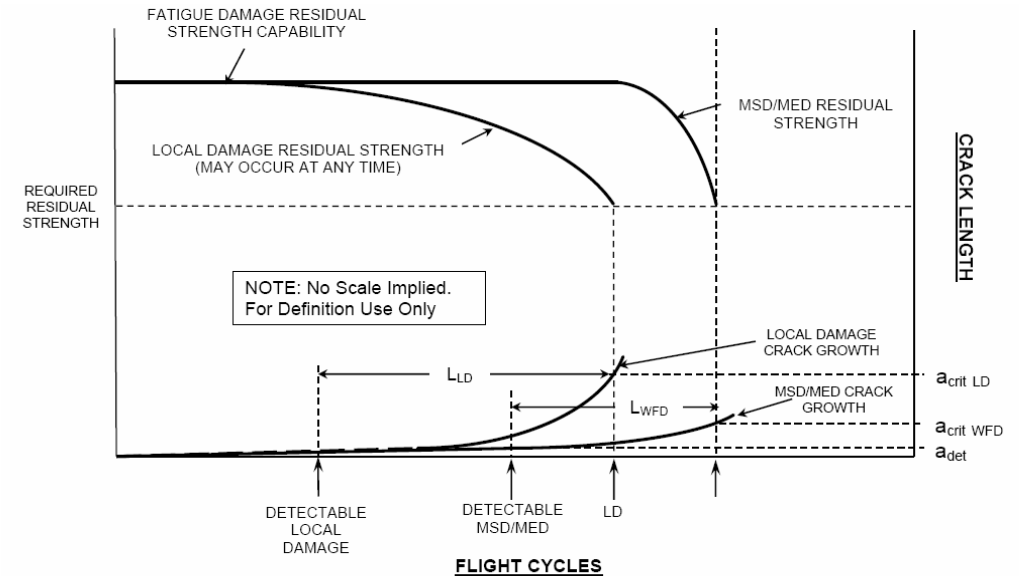

Figure 6. Comparison between local damage and MSD behavior.[6]

3.2 Probabilistic Assessment of Structures Susceptible to MSD

The probabilistic assessment procedures can be divided in different stages according to Garcia,[8] fatigue crack initiation and probabilistic crack propagation. For crack initiation it is assumed that each potential damage site has two fatigue crack locations, generally at 3 and 9 o´clock positions. For each location a lognormal or Weibull distribution is defined by means of the SN fatigue curve. In order to simulate the probabilistic nature of fatigue crack growth, the Monte Carlo method has been extensively used. The growth of each fatigue crack location is estimated through LEFM equations, stress intensity factor takes into account the interaction of adjacent cracks using compound process, and the modified Paris equation or a better model is considered to crack growth ratio calculation. The simulation process stops by defining a failure criteria, generally it is used the critical crack size or residual strength diagram (e.g. net section yielding). The flowchart below shows the required steps to perform the probabilistic MSD assessment. Figure 7 shows an outline of the MSD assessment approaches.

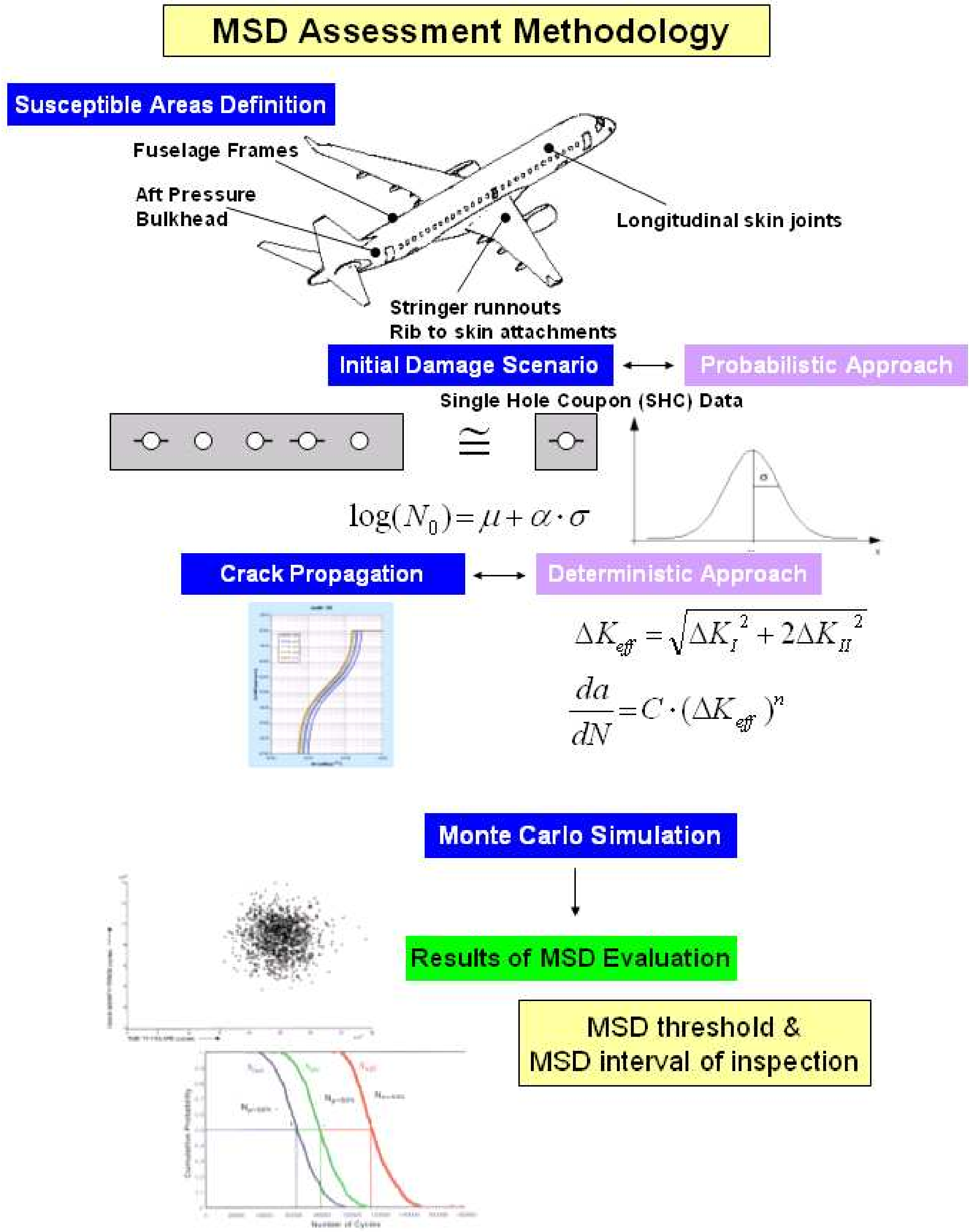

Figure 7. MSD Analysis Procedure.

4 MSD SIMULATION APPROACHES

Due to the high complexity that involves the modeling of multiple cracked structures in terms of fatigue crack growth and correlation with experimental data, the MSD behavior is difficult to be predicted by current available Linear Elastic Fracture Mechanics (LEFM) theory. Many efforts have been done in past decades by federal regulatory agencies, aircraft industry, academies as well as fatigue committees to allow better understanding and improving numerical methods to avoid and prevent aging aircraft failures. In the present work the authors present a biography revision of already developed models and numerical procedures to be applied in the modeling of MSD in aircraft structures. A brief discussion of simplest model based on LEFM Link-Up model is first addressed. The modern and more accurate model based on Crack Tip Opening Angle (CTOA) is discussed in some detail.

4.1 Link-Up of Adjacent Cracks

The residual strength of a structure with MSD can be verified by the interaction of adjacent cracks when the plastic zones touch. This simplified model was introduced by Swift[9] and is today known as Plastic Zone Touch (PZT) model. Basic concepts of LEFM are used in PZT model. In the boundaries of Small Scale Yielding (SSY), the Irwin's approach can be used to the first order estimation of plastic zone size, according to Anderson.[10]

$$r_y = \frac{1}{2\pi}\left(\frac{K_1}{\sigma_y}\right)^2 \quad (1)$$

Since the residual strength of the major aluminum alloys is limited by net section yielding criterion, it is reasonable to suppose that the leader crack link-up with MSD will occur when the stress achieves the material yielding strength, this criterion was proposed by Swift as already mentioned. Figure 8 shows the plastics zones sizes of the leader crack, called (R_2) and the MSD crack (R_1), according to Ciliato.[11]

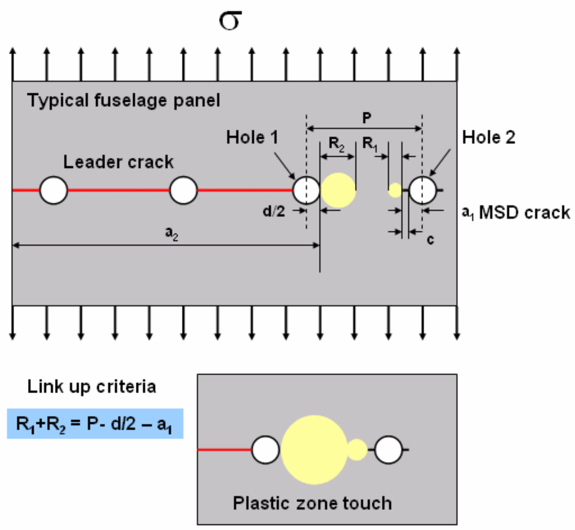

Figure 8. Leader and MSD cracks defined in Link-Up model.[11]

The link-up will occur when both plastics zones defined by R_1 and R_2 touch, therefore:

$$R_1 + R_2 = P - \frac{d}{2} - a_1 \quad (2)$$

The Irwin model to first order estimation of plastics zones sizes, R_1 and R_2, can be used as described below:

$$K_1 = \beta_h \cdot \beta_{I1} \cdot \sigma \cdot \sqrt{\pi \cdot a} \;\; \& \;\; K_2 = \beta_s \cdot \beta_{I2} \cdot \sigma \cdot \sqrt{\pi \cdot a} \quad (3)\ \&\ (4)$$

By substituting these equations in 2, the following expression can be found:

$$\sigma_R = \sqrt{\frac{2 \cdot \sigma_y^{\,2} \cdot \left(P - \frac{d}{2} - a_1\right)}{\beta_h^{\,2} \cdot \beta_{I1}^{\,2} \cdot a_1 + \beta_S^{\,2} \cdot \beta_{I2}^{\,2} \cdot a_2}} \quad (5)$$

As discussed by Ciliato, the Link-Up model introduced by Swift does not take into account the stable crack growth before the rupture. Thus, its application for ductile materials takes to excessively conservative results. Therefore, the PZT model has been used in initial comparative analyses between different geometries and materials, instead of final projects.

4.2 Crack Tip Opening Angle (CTOA)

During an airframe structural integrity program conducted by National Aeronautics and Space Administration (NASA) in collaboration with FAA, residual strength analysis of laboratory specimens and stiffened panels were predicted quite well from the Crack Tip Opening Angle (CTOA). The CTOA was introduced by Wells[12] in 1963 and according to Newman et al.,[13] this fracture criterion has been experimentally verified to be a valid criterion to mode I stress state in thin plates. This criterion has been demonstrated to be valid for predicting the link-up of a lead crack with small MSD adjacent cracks. NASA Langley Center also concluded that the ductile tearing is an important parameter to be evaluated, that could not be predicted by LEFM and J-Integral scope. For this evaluation, the elasto-plastic crack growth simulation criterion showed to be efficient. The stable tearing should be an intrinsic characteristic of the elasto-plastic materials, due to plastic deformation occurrence during the unloading phase. Another important point to be considered is the state of stress. Ciliato discussed in his work, the concept presented by Newman in 1983 that introduced a mixed state of stress, called Plane Strain Core, to take into account the effects of triple state of stress in the crack tip.   The CTOA defines the displacement field in the crack tip and is considered a local parameter. It became to be an alternative criterion to J-Integral and has been extensively used in the ductile fracture researches in 80´s and 90´s decades, as discussed by Ciliato. Basically the CTOA criterion defines that the opening angle remains constant during stable crack propagation. According to Chen, Wawrzynek e Ingraffea[14] and suggested by Newman, the CTOA criterion is mathematically defined by:

$$CTOA = 2 \cdot arctg \frac{\delta}{2 \cdot d} \quad (6)$$

Ciliato based his study based on laboratory experiments data performed by NASA Langley Center, and numerical simulation in order to predict the residual strength of complex and real aircraft fuselage structures. The tests were conducted using MSD specimens considering five different crack configurations. The specimen material was AL 2024-T3 2.3mm plate.

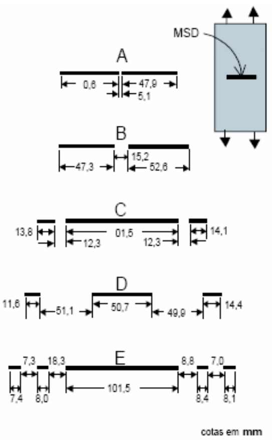

Figure 9. MSD scenarios.[10]

Next figure illustrates the numerical results obtained by Ciliato, compared against the experimental data obtained by NASA Langley Center.

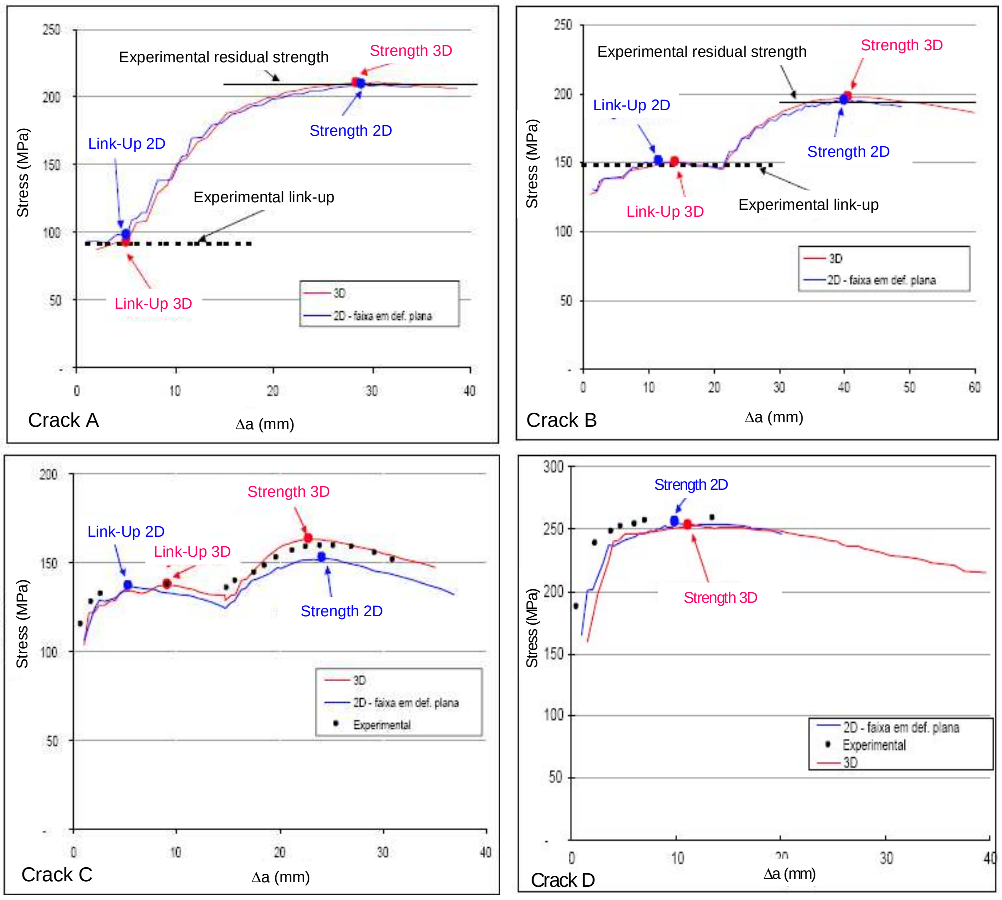

Figure 10. Comparison between numerical and experimental results for different MSD cracks.[11]

5 CURRENT REQUIREMENTS REGARDING MSD

In the Aging Aircraft Safety Act (AASA) congress of 1991, the FAA required to promulgate a rule to assure continuing airworthiness of aging aircraft. One of the required actions was to demonstrate that maintenance of the aircraft structure, skin, and other age-sensitive parts and components have been adequate and timely enough to ensure highest degree of safety, in order to avoid catastrophic failures.

The Aviation Rulemaking Advisory Committee (ARAC) was established to provide advice and recommendations to the FAA for safety rulemaking activities. In response to the act, FAA issued the Aging Aircraft Safety Rule (AASR) in 2005 to require damage tolerance based inspections. The FAA´s Aging Airplane Safety Program for structures was one of the results of an ARAC tasking. The major elements of the program are:

- mandatory modification program;
- structural maintenance program guides;
- corrosion prevention control program;
- review and update Supplemental Structural Inspection Document (SSID); and
- Repair Assessment Program (RAP).

The SSIDs and RAP typically applied to limited structures on the eleven airplanes models described in section 1. Some definitions used in SSIDs are described below according to Federal Aviation Administration:[(15)]

Base Line Structure: Structure that is designated under the original type certificate or amended type certificate for the airplane model.

Alteration: Design change made to baseline structure.

Modification: For the purpose of these rules, synonymous of alteration.

The Aging Airplane Safety Rule requires implementation of damage tolerance based structural inspection programs for fatigue critical structures.

Fatigue Critical Structure (FCS): Airplane structure that is susceptible to fatigue cracking that could contribute to a catastrophic failure. The FCS could be baseline structure or structure added by an alteration.

Based on concepts above, the FAA issued an operational rule requiring operators to incorporate a structural maintenance program to their maintenance program with a Limit of Validity (LOV) for structural maintenance program. The concepts and procedures described above were issued by FAA as a Federal Rule called FAA Part 26 – Continued Airworthiness and Safety Improvements for Transport Category Airplanes.

6 GENERAL COMMENTS AND CONCLUSIONS

According to presented in this work, the MSD study gained notoriety since the accident of Aloha Airliners B737, and has been subject of industrial, governmental and regulatory agencies researches during past decades with the aim to improve safety of high cycled airplanes. As results of those researches, studies and in service experiences, new federal rules have been proposed by FAA in order to improve the continued airworthiness requirements of aging aircraft. The rules, new actions to be followed, as well as, new means of compliance are presented on PART 26 document issued by FAA. In terms of analytical and numerical techniques to prevent the MSD failure, the Link-Up model, first introduced by Swift, and the modern and robust approach based on CTOA have been worldwide used in the study of aging aircraft. The Link-Up approach is a simplest and easily implementing model, based on fundamental concepts of LEFM. Its application is limited to initial and simple analyses and it is not recommended for ductile materials evaluation, getting to highly conservative results. For high complex structures and ductile materials, the CTOA criterion is recommended by many authors. It was proved to allow better fit between numerical and experimental data, and it was the criterion chosen by NASA to MSD assessment evaluation. The authors as members of ITA´s Aeronautical Engineering Department and their interesting for fatigue and damage tolerance studies, have been expending efforts in order to understand and evaluate the current available methodologies as well as the steps to implement numerical routines, develop engineering tools and procedures in order to predict the MSD effect in future aircraft developments.

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