PROGRESSIVE FAILURE ANALYSIS APPROACH FOR ESTIMATING MATERIAL FRACTURE TOUGHNESS (REDUCING TIME & COST OF TESTING)

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ABSTRACT

In the field of linear elastic fracture mechanics, the fracture toughness is an important parameter for safe-life estimation of structural parts. The plane strain fracture toughness, KIc, is thickness independent and it can be obtained through the ASTM-E399 testing standards. The ASTM standards and procedures require detailed specimen preparation, pre-fatiguing the notch, and fatigue crack growth rate measurements. These tests are expensive and time consuming. Progressive failure analysis is therefore used to estimate material fracture toughness. This approach will combine finite element analysis (FEA) with a General Optimization Analysis (GENOA) software [1] to update material properties as damage occurs. The proposed approach will consider the static properties obtained from the stress-strain curve as an input to assess the crack tip stress and strain fields. The GENOA Progressive Failure Analysis (PFA) is based on material degradation concept throughout the FEA model as the load magnitude increases. The structural stiffness will decrease as the load increases, new properties will be assigned to the FEA elements, and the process will continue until structural stiffness is depleted. The plane strain fracture toughness is calculated by establishing the load versus displacement. The maximum load is used to calculate the fracture toughness through the stress intensity factor equation. To verify the validity of this approach several aluminum alloys were selected and their static properties were obtained through MIL-HDBK5. The mode I load versus displacement for each specimen was extracted from the progressive failure analysis and the maximum load was captured. The estimated critical stress intensity factors were in good agreement with the test data obtained through the NASGRO [2] database. The application of this work on aircraft and aerospace metallic alloys is in progress. Moreover, the extension of this concept to non-metallic materials (composite and foam) is promising. Currently, a preliminary progressive failure analysis task for the Shuttle Columbia external tank foam failure is underway.

1 INTRODUCTION

Extensive efforts to analytically identify critical value of damage in materials have been undertaken in recent years. The primary finding of most of these investigations was that macroscopic fracture was usually preceded by an accumulation of the different types of microscopic damage and global damage occurred by the coalescence of this small-scale damage into macroscopic cracks. Additionally, it was generally found that analyses based on classical fracture mechanics could not adequately model the damage growth and did not provide a satisfactory degree of predictive capability without conducting laboratory tests.

Damage stability is influenced by both local factors, such as constituent material properties at the location of damage, and global factors, such as structural geometry and boundary conditions. The interaction of these factors, further complicated by the numerous possibilities of material combinations, crack geometry, and loading conditions, renders the assessment of material damage progression very complex. This complexity makes it difficult to identify and isolate all significant parameters affecting damage stability without a model based computer code capable of incorporating all factors pertinent to determining structural fracture progression, fundamental to evaluating the durability and life of structural components.

The stress-strain curves obtained for many aerospace and aircraft material revealed the existence of direct relationship between fracture toughness and material ductility. Material ductility can be defined as the area under the full stress-strain curve. Recently, Dr. Farahmand from the Boeing Company [3,4] has been estimated material fracture toughness by using the area under the full stress-strain curve. His methodology is based on the energy balance approach, which first was proposed by the Griffith theory of brittle fracture. With the extended Griffith theory approach, the energy absorption rates for plastically deforming material at the crack tip and near crack tip are derived from the energy under the full stress-strain curve and used to extend the Griffith concept of brittle fracture to Fracture Mechanics of Ductile Metals (FMDM) theory. The importance of this approach is to reduce the cost and time of ASTM testing. The progressive failure analysis is another promising approach that can estimate material fracture toughness without conducting tests. The proposed progressive failure methodology is utilized to establish load versus displacement for the center crack specimen and the maximum load is used to estimate the mode I fracture toughness through the stress intensity factor equation.

2 MATERIAL DEGRADATION AND STRUCTURAL FAILURE

GENOA-PFA implements a progressive-failure methodology, the basic concept of which is that a structure fails when flaws that may initially be small (even microscopic) grow and/or coalesce to a critical dimension such that the structure no longer has an adequate stiffness to avoid catastrophic global fracture. Damage is considered to progress through five stages: (1) initiation, (2) growth, (3) accumulation (coalescence of propagating flaws), (4) stable propagation (up to the critical dimension), and (5) unstable or very rapid propagation (beyond the critical dimension) to catastrophic failure. The computational simulation of progressive failure involves formal procedures for identifying the five different stages of damage, quantifying the amount of damage at each stage, and relating the amount of damage at each stage to the overall behavior of the deteriorating structure. In this report center crack specimens in aluminum plates will be loaded monotonically in mode I. Crack tip stresses will be estimated through finite element modeling and compared with material allowables. When the applied load magnitude is sufficient, stable crack growth will occur. The increase in crack length will cause structural stiffness to reduce. Material degradation and structural failure is eminent when the load magnitude and crack length are sufficient as shown in Figure 1.

3 METHOD OF APPROACH

A center crack in a plate was modeled using the PATRAN mesh generator as illustrated in Figure 2. To simulate a natural crack, the crack tip was 0.005 inch wide. Crack tip and other specimen dimensions are also shown in Figure 2. Based on the previous finite element analyses the crack tip stresses were shown to be sensitive to the mesh density in that region. Extensive finite element analyses revealed strong dependency between the calculated critical load (causing structural failure) and element size at the crack tip. It was concluded that with the presence of a refine mesh at the crack tip with rectangular elements aspect ratio of less than 4, a threshold value can be obtained where crack tip is no longer sensitive to the number of elements. Figure 3 shows the result of mesh size and aspect ratio sensitivity study conducted for a center crack plate, where a threshold value is obtained for several aspect ratios. With the progressive failure analysis approach, the crack length is constantly increased, resulting in the reduction of structural stiffness. The mesh density at the crack tip is therefore kept constant throughout the net section region (Figure 4).

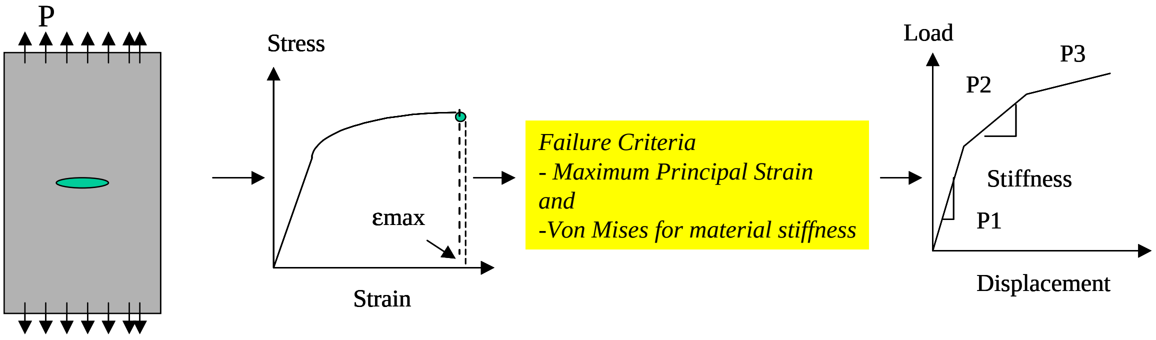

Figure 1: Material degradation and structural stiffness reduces as the applied load increases

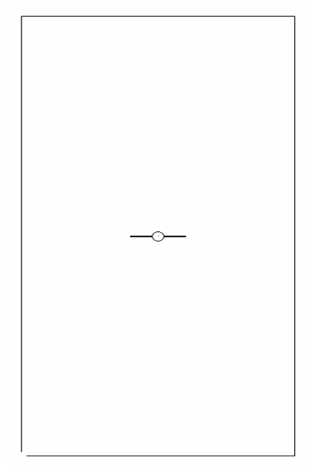

Figure 2: Specimen Geometry

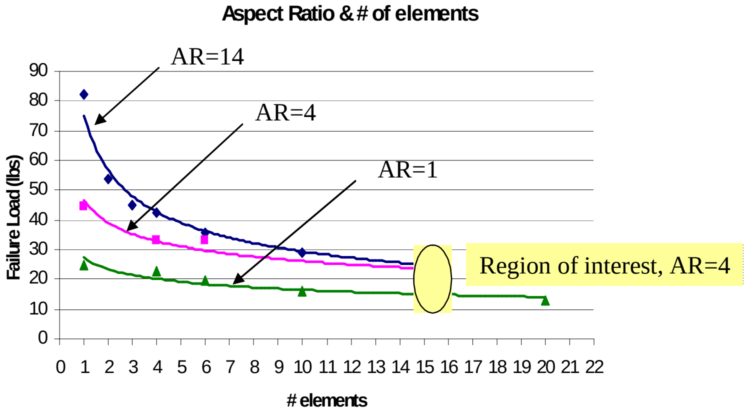

Figure 3: Mesh Size Sensitivity Study

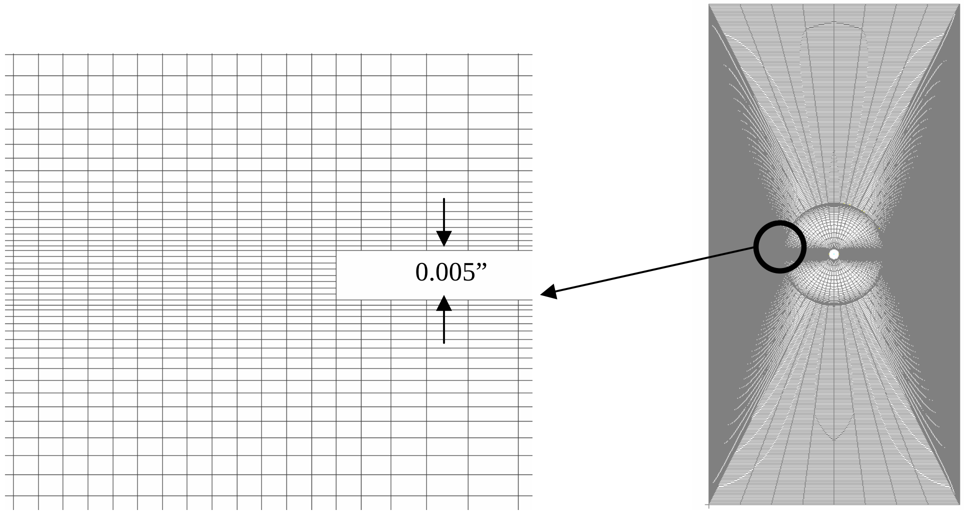

Figure 4: Crack Tip & Specimen Meshes

4 PROGRESSIVE FAILURE ANALYSIS RESULTS

Two aluminum alloys were selected for this study and progressive failure analysis approach was implemented. Full stress-strain curves for 2024-T351 and 7075-T62 aluminum alloys were required in order to assess the crack tip failure based on the maximum strain theory criteria (Figure 5). The road map to the crack tip failure and progressive failure that can lead into the structural failure is shown in Figure 6. The maximum loads leading to final failure were recorded in each case and they were used to calculate the critical value of stress intensity factor via eqn (1).

$$K_{IC} = (P / Bw\ )\, f(a/w) \qquad\qquad f(a/w) = \sqrt{\pi a \sec(\pi\, a/w)} \qquad\qquad (1)$$

Table 1 shows the calculated stress intensity factors for 2024-T351 and 7075-T62 aluminum alloys and were compared with available test data extracted from NASGRO database. Good agreement between analysis and test data can be seen.

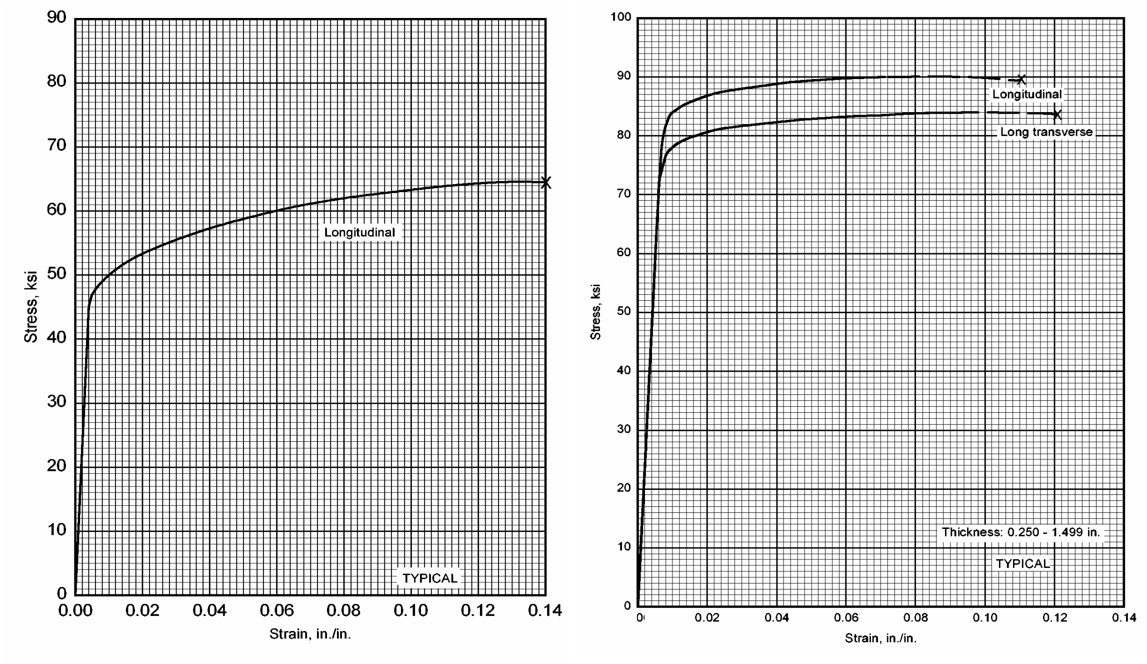

Figure 5: Stress-Strain curves for 2024-T351 and 7075-T62 – MIL-HDBK-5

	Fracture Toughness Estimation Kc (ksi-vin)	
	NASGRO	PFA Analysis
Aluminum Alloy 2024-T351 Thickness: 1.5"	31	29
Aluminum Alloy 7075-T62 Thickness: 1.5"	21	20

Table 1: Stress Intensity Factors for 2024-T351 & 7075T62 Aluminum Alloys

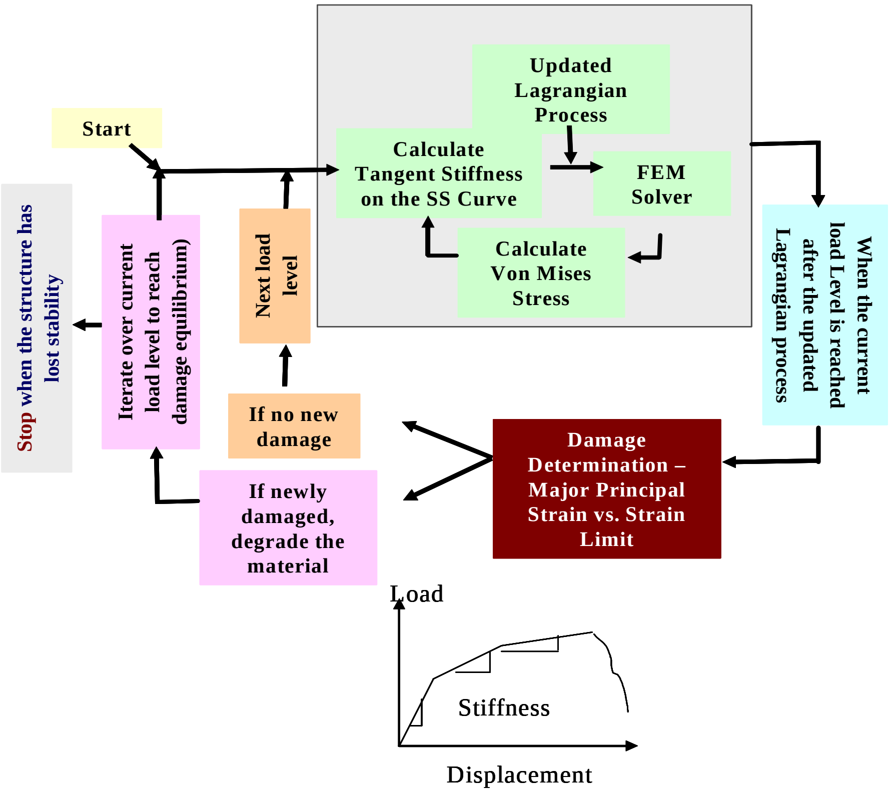

Figure 6: Road Map to Crack Tip Failure

5 SUMMARY AND CONCLUSION

An attempt was made to estimate the material mode I material fracture toughness value through the progressive failure analysis approach. 2024-T351 and 7075-T62 aluminum alloys were selected for this study. Results of analyses were in good agreement with the test data obtained through the NASGRO database. The proposed analytical method will use the maximum strain theory for crack tip failure criteria where material at the crack tip and stiffness degradation take place. Currently, the capability of this method is limited to the metallic material, that do not neck and the final failure occurs at the ultimate strength of the material (Figure 5). Crack tip failure behavior for this type of material can be estimated by the maximum strain failure and results indicated that analyses and test data are in good agreement with each other. Future work will extend the application of the progressive failure method to other material. Work is currently in progress to apply this methodology to the foam material as part of the Return to Flight task.

6 REFERENCES

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