First International Conference on Damage Tolerance on aircraft Structures
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Problems of Laboratory Tests for Durability Evaluation of Full-Scale Structures

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Key words: Durability evaluation, Fatigue life, Laboratory test, Actual structural response, Open hole and rivet

Abstract *In this paper, discussion is made on the difference between the simplified component tests conducted in the laboratory and the full-scale fatigue test with actual loading conditions. Also, the difference between analytical models and assumptions that are used for the prediction of fatigue strength and actual structure response is examined.*
From the above discussions, several points that we have to pay attention to simulate the actual structure response by the laboratory tests are examined.

1. INTRODUCTION

The fatigue design methodology of the aircraft structures that evolved from Safe-life to Damage Tolerant (DT) design concept which essentially based on fail-safe design concept had largely contributed to enhance the safety level of not only aircraft but also various fields such as atomic power plant, and so on.
Concerning the aircraft, for example, in the accident of Comet I in 1954, half a century ago, the fatigue crack extension in the primary structure led to the immediate catastrophic mid-air explosion under maximum stress condition of normal pressurization cycles. However, today, the aircraft could land in safe, even it received large-scale damage in fuselage as seen in Aloha Airline in 1988. Also, in the JAL accident in 1985, the aircraft could stay in the air for 32 minutes after the decompression and even total loss of hydraulic oil and vertical fin. And also in the accident of American Airlines in 1989, more than 60 % of on-board could survive after the similar critical condition as JAL accident. In this way, the modern design technology based on DT concept largely contributed to enhance structural safety.
On the other hand, such new technologies as application of new types of composite materials, new processing technologies as vacuum assisted resin transfer molding (VaRTM), friction stir welding (FSW) and aging aircraft problems with wide-spread fatigue damage (WFD) are raising some challenges to the application of DT concept. In this paper some considerations are made on the application of DT concept.

2. THE STRONG AND WEAK POINT OF APPLICATION OF *ANALYTICAL METHODS* TO CRACK PROBLEMS

The evaluation of DT characteristics of the structures should be conducted by thoroughly reliable analysis and experimental verification tests simulating the actual structure and loading conditions with sufficient extent.

One of the Structural Significant Items (SSI) which DT concept should be applied may be the joint structures, because more than 80% of structural failure originated from any kinds of joint components. For failure origins other than joint components such as tool marks, notches, holes, corrosion damage or material defects, estimation of damage extension or remaining life can be conducted by linear fracture mechanics method with sufficient accuracy except very beginning stage of damage extension. The author discusses here mainly on structural joint problems that should be taken care of when to apply DT concept from the laboratory study results.

2.1 On Damage Extension Prediction by Analytical Method

2.1.1 Merit of Analytical Method

It is effective and reasonable to use Stress Intensity Factors (SIF) as the fracture mechanics parameter for the prediction of crack propagation.

The advantage of analytical method is obvious when it is used with sound data on boundary conditions, fracture toughness and reliable material constants included in the prediction equations. For the different boundary condition problems, the analytical method gives good predictions instantly by changing the parameters in the equations. In fact, it is well known that the growth rate equations can predict well the crack behavior initiated from an open hole in the broad range of ΔK except the initiation phase.

2.1.2 Weak Point of Analytical Method

The prediction equation always automatically gives us the answer when we input the data into computer regardless of the quality of the data, namely whether they correctly represent the actual boundary and initial condition or not. If we carelessly use these results to predict the behavior of the damage and life ignoring the difference between the models used to derive the prediction equation and the actual structures, it would mislead to an erroneous results as shown by the following examples.

Example 1:

It is questionable to apply the results derived analytically from the cases as shown in Figure 1 to the fatigue cracks emanated from fasteners, especially in the crack initiation phase because of the following reasons:

(1) The difference of rivet hole and open hole:

* Intuitive difference;

Sometimes we see the papers discussing the crack propagation behavior such as crack growth rates and link-up conditions from the rivet holes based on the test results of open-hole specimens. But they are the completely different problems.

- For open hole, the more holes mean the shorter life, because of ligament stress increase.
- For rivet hole, the more holes mean the longer life, because the stress around the holes decreases.

* Difference of fatigue crack initiation cause and extension mechanism.

- For open hole, crack nucleation and growth rate largely depend on the stress concentration factor of the hole.

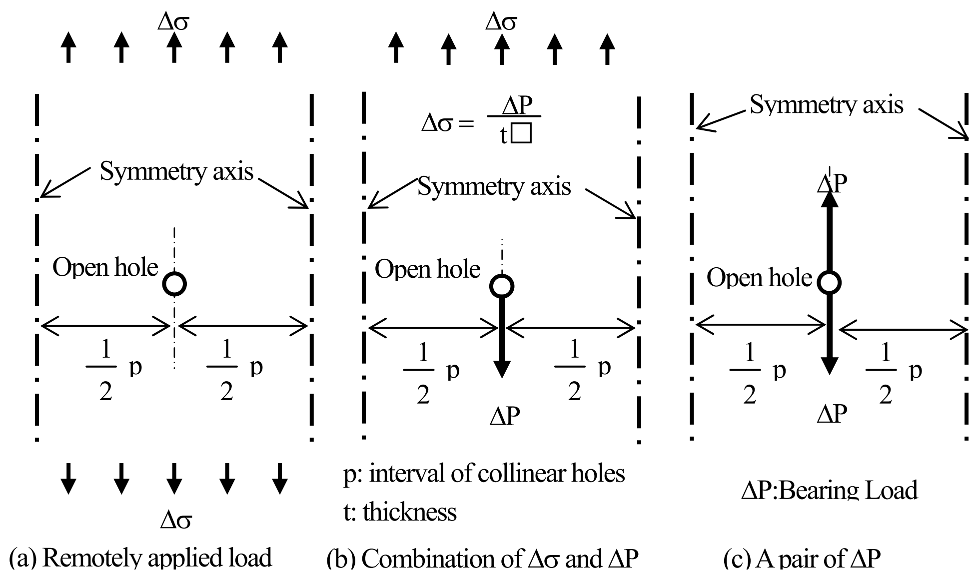


Figure 1 Collinear open holes subjected to different types of fatigue load

- For rivet hole, crack nucleation and propagation depend mainly on the clamping condition of the fastener [2,3] (see, Figure 2):
  * For loose clamping, stress state and crack propagation behavior around the rivet hole can be interpreted as the bearing stress condition at the hole edge. Cracks initiate from the hole edge and propagate perpendicular to the loading axis.
  * For tight clamping, crack initiates mainly by fretting and the propagation is strongly affected by the thickness-wise residual compressive stress by clamping. Cracks initiate from either hole edge or away from the hole depending on the tightness of the fastener.

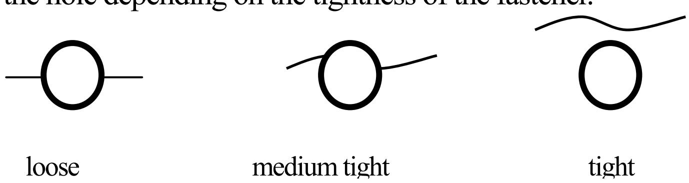


Figure 2 Fastener tightness and fatigue crack initiation site (Case: button head rivet)

As discussed above, the crack behavior, especially at the initiation phase, depends largely on the crack initiation mechanism. And also, clamping force affects the material deformability near the fastener.

Tight clamping arrests the crack extension by suppressing the opening displacement of the small cracks in the vicinity of the rivet holes. Therefore, one cannot ignore the effect of thickness-wise compressive residual stress on the evaluation of SIF of a crack located in this affected zone (see, Figure 3).

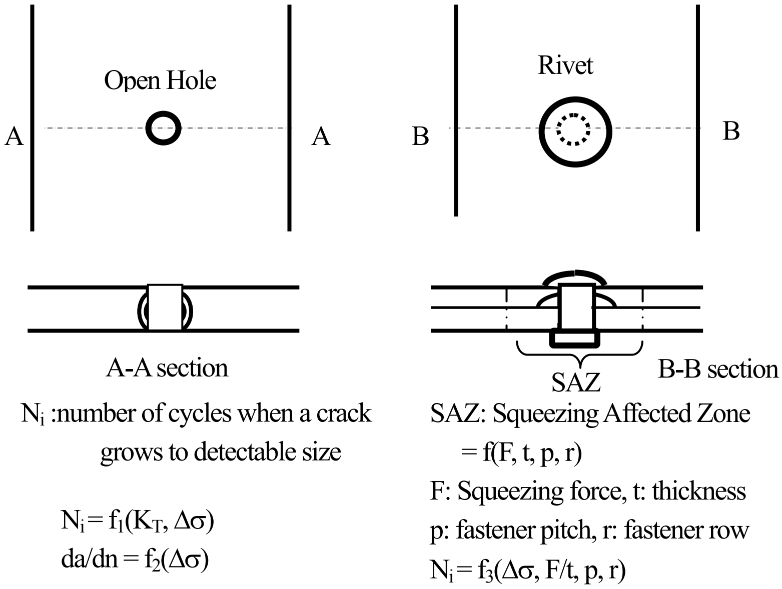


Figure 3 Difference of open hole and fastener on N_i and da/dn

Example 2:

As another example showing a big difference between analytical and actual crack behavior of the structure, we can recall the case of Dan Air accident in 1977[4].

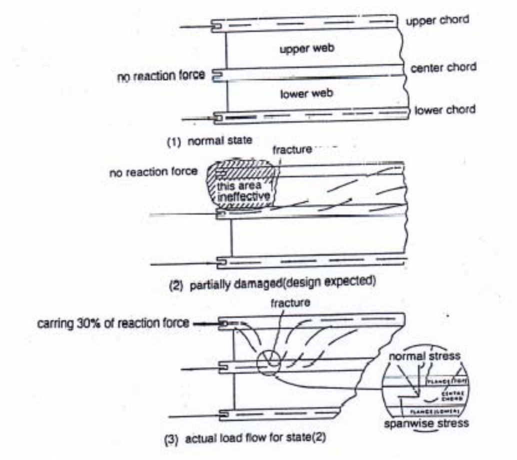


Figure 4 Example of inconsistency of designer's intention and structural response
(Fracture of horizontal stabilizer[4])

As shown in Figure 4, the expected force flow obtained by analysis for reinforced structure at the moment of redesigning was completely different from that of the actual structures, and the fail-safe concept that the designer expected did not work effectively. One of the reasons for this was that they used new materials with higher rigidity and strength for the purpose of reinforcement, and the difference of rigidity between stainless steel and conventional aluminum alloy became the cause of another new crack. The load transfer mechanism between different materials is hard to take account by the analysis.

3. PROBLEMS OF EXCESSIVE DEPENDENCE ON TEST RESULTS

The experimental results obtained by the tests conducted under the same load spectra using the full-scale model of the actual structures give us the most reliable results. However, those tests are not easy to conduct because of cost and time. Consequently, the durability of actual structure is generally estimated using various levels of subscale components or coupon specimens.
Those component tests should be conducted carefully by keeping the following issues in mind.

3.1 Failure of Durability Evaluation Using Structural Components

- Development Test of Comet I
  Pressurizing test for cabin structure was conducted using partial fuselage structure fixed to the rigid wall. As a result, the apparent strain and displacement of the tested specimen indicated smaller values than the actual full-scale structures subjected to the same pressurization cycles. Consequently, the deformation and the strength of the actual structures were under-estimated.
- Problem of Fatigue Life Estimation of Single Lap Joint Structures from Laboratory Test Data.
  We have to pay attention on the following peculiar phenomena that are apt to occur in the laboratory tests.
  - When we evaluate the fatigue life of lap joint structure from the component test results conducted as the laboratory test, it is necessary to suppress the out-of-plane deformation at the side edge of the specimen, otherwise the resulting fatigue life always gives much shorter than that of full-scale structures[5] (see, Figure 5).

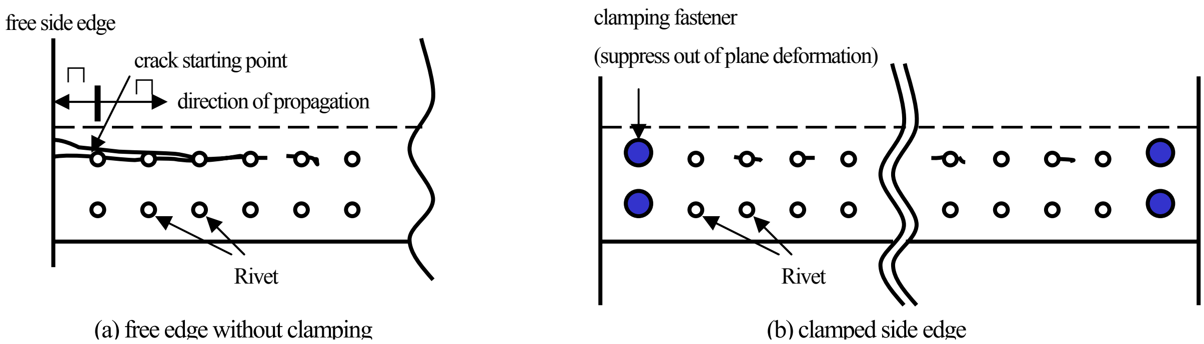
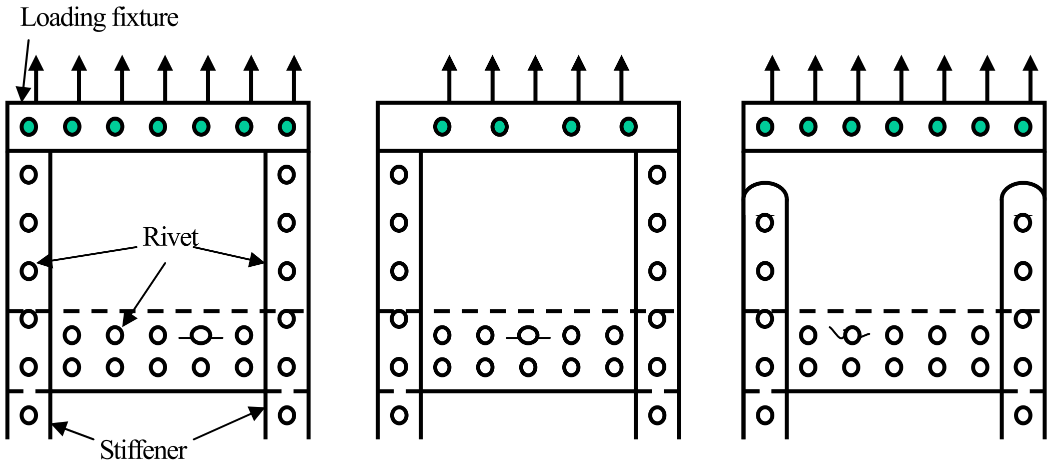


Figure 5 Consideration of side edge effect

  - When we evaluate the crack arresting effects of the stiffened panel structures, we may not evaluate correctly if the loading end of the stiffeners were clamped rigidly.

Constant displacement at the loading end means much higher load sharing of the stiffeners than skin panels because of flexibility difference among them[3]. As a result, fracture always takes place at the stiffeners first, even if the initial cracks were introduced at the skin panels (see,Figure6).



(a) full clamping at end fixture (b) partial clamping at end fixture (c) using short stiffener

Figure 6 Load end consideration of stiffened panel in laboratory tests

- We should recognize that the uniaxial loading test of the single lap joint in the laboratory can not correctly simulate the actual pressurized barrel type fuselage. The effect of loading axis offset and out-of-plane deformation cannot be coincided completely for the two cases even if large aspect ratio of the panel specimen is chosen[3].
- Critical crack length obtained by pneumatic pressurizing test is generally short compared with that obtained by hydraulic pressurizing or uniaxial cyclic load tests.

$$a_{c,p} < a_{c,h} \text{ or } a_{c,t} ,$$

where, $a_{c,p}$, $a_{c,h}$ and $a_{c,t}$ are critical crack length by cyclic air pressure, water pressure and tensile fatigue load, respectively.

This is because the air holds high potential energy, even at the critical moment of unstable failure and induces bulging deformation. Namely, unstable fracture takes place under the mixed mode of $K_{\square}$ and $K_{\square}$ in this case.

In the case of water pressure, the effect of $K_{\square}$ is negligibly small, because the water is considered to be incompressible fluid and bulging effect is small. And in the case of tensile fatigue test, fracture occurs simply under $K_{\square}$ mode.

From all above reasons, we have to satisfy the following conditions correctly based on the strain measurement of actual structures when we predict the fatigue strength of the full-scale structures from the test results conducted in the laboratory:

- Strain distribution of inner and outer surface of the skin panel,
- Strain distribution of the skin panel and stiffener in the bay.

Figure 6 shows some examples adjusting the load end conditions to obtain the desirable stress distribution in the stiffened panel structures.

4. DISTRIBUTION OF INITIAL FLAWS TO BE GIVEN IN FULL-SCALE DT TEST

In order to assure the integrity of aircraft structure, it is generally recommended to conduct 2-lifetime full-scale fatigue test and 1-lifetime DT test. In the full-scale DT test, it is necessary to introduce artificial flaws at the sites that are critical from the point of structural integrity. It is therefore desirable that the distribution pattern of size and number of these flaws simulate natural corrosion and fatigue damage as much as possible. As the distribution pattern of size and number of these flaws affects largely on the resulting fatigue life, it is recommended to obtain those data based on the teardown inspection of the aging aircraft or the investigation of an accident aircraft caused by WFD or related structural damage.

The author obtained the data shown in Figure 7 on the distribution pattern of size and number of flaws from the MSD observation of aft-bulkhead fractured by WFD in 1985[8] and numbers of fatigue fractured wide sheet specimens with lap joint. Figure 8 shows the crack size distribution at the mis-repaired area (rivet site from #30 to #82) of aft bulkhead.

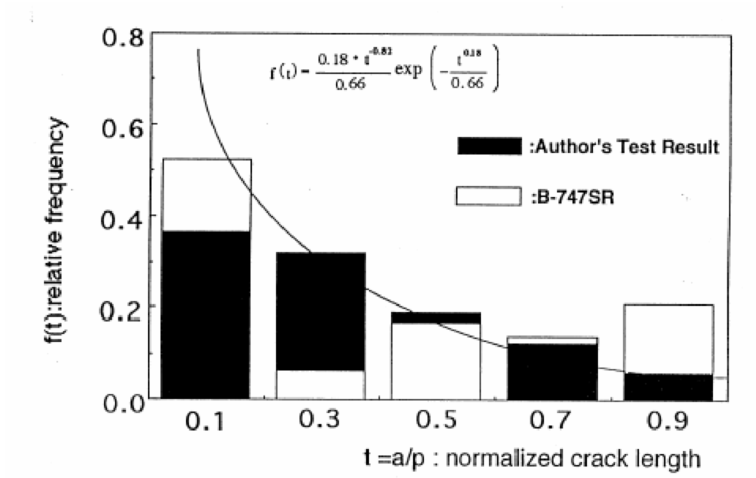


Figure 7 Crack size distributions of multi-site damaged structures

The result shown in the Figure was simulated by two-parameter Weibull distribution functions as given in Equation 1.

$$F(t) = A_0 \frac{0.18t^{-0.82}}{0.66} \exp\left(-\frac{t^{0.18}}{0.66}\right)$$

A_0 : Severity Factor, $0 < A_0 <$ □

In case the Equation is used to introduce artificial flaws for full-scale DT test, we have to multiply a certain constant value (A_0), which must be less than unity.

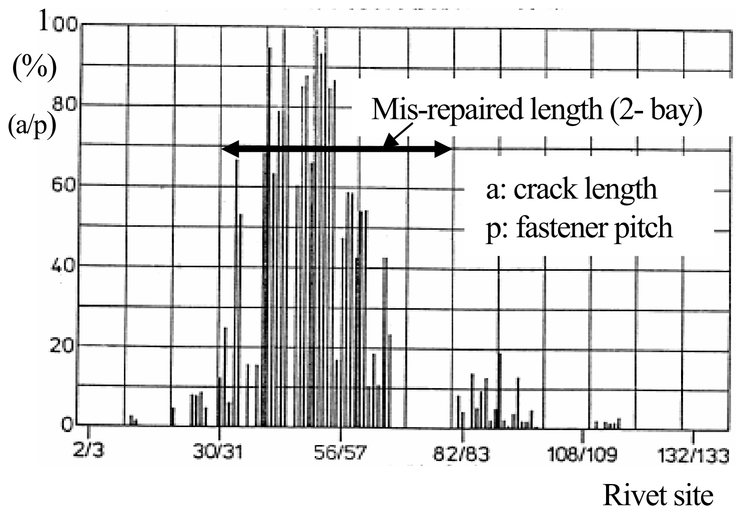


Figure 8 Crack size distribution of fractured bulkhead panel (JAL Accident in 1985 [8])

The constant A□ can be determined arbitrarily by the DT test planner. The equation in Figure 7 is the case where A□= 1, because it was obtained by the measurement after the final failure.
Equation 1 suggests a realistic proposal for size and number of initial flaws for full-scale DT test. However, in order to make the result of DT test more reliable and realistic, international collaboration for the acquisition of damage distribution data from the teardown inspection of various types of aircraft is highly recommendable.

CONCLUDING REMARKS

In this paper, the author pointed out the risk to be accounted in the evaluation of damage tolerant characteristics of full-scale structure using the results obtained by laboratory test or computer analyses.
It is indispensable to examine the reliability and limitation of these results when you apply them to the damage tolerant evaluation methodology, because the laboratory tests and analysis results are usually derived based on the simplified boundary conditions that are different from those of actual structures in many cases.
From the similar viewpoint, the author also emphasizes that the teardown inspection data of aging aircraft and the investigation data of accident aircraft caused by structural fatigue should be collected and utilized for the evaluation of damage tolerant characteristics of full-scale structures.

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