Fatigue crack growth prediction and verification of aircraft fuselage panels with WFD

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Widespread Fatigue Damage (WFD) is recognized as one of the biggest threats on structural integrity, especially for aging aircraft. Its evaluation provides a tough challenge for typical aircraft damage tolerance design and analysis because of many structural detailed differences in stress levels, local loading and assembly forms. Three main factors should be considered in WFD problems: crack cracks interference, inner-stress redistribution and overlap between cracks. Independent cracks propagation analysis will induce incorrect results in WFD prediction, and the traditional engineering method face the difficulties to obtain stress intensity factors and interference effects of multiple cracks. Comparatively numerical simulation methods are favored by aeronautical engineers owing to its independence of crack geometries. Engineers mainly apply Finite element method to evaluate the airworthiness of metallic structure in Civil Aircraft, yet how to build a modeling to analyse the coordinating and automatic propagation between multiple cracks is the key and complicated point to predict WFD life.
Based on the secondary development function of Abaqus, this paper will provide an efficient modeling to analyse the fatigue cracks growth life of aircraft fuselage panels with WFD, besides the test approach of panels subjected to internal pressure load is studied to verify the feasibility of the proposed modeling.
Based on linear fracture mechanical theory, the crack pre-growth length Δa for WFD structures is limited as $\Delta a \geq \Delta a_{\min}$. Supposing the crack angle at step *i* is written as CPd_i, the propagation length of each crack is:

$$\Delta a = \begin{cases} f(\min_{i=1}^{n} \Delta N) & \max(CPd_i) \leq 15 \\ f(\Delta N_{i=index(\max_{i=1}^{n}(\Delta\theta))}) & \max(CPd_i) > 15 \end{cases} \tag{1}$$

Where ΔN is the cycle number when every crack propagate the minimum step length; $f(x)$ is crack propagation function; *n* is the number of crack tips; $index(\max_{i=1}^{n}(\Delta\theta))$ is the crack number of maximum crack angle .
The stress intensity factor K of structures under constant spectrum loading can be considered as constant in small propagation length; Conversely, K depends on loading value for the structures under random spectrum. In order to decrease the numerical calculation amount, K can be obtained as following:

$$K_{j+1} = \frac{\sigma_{j+1}\sqrt{a_j}}{\sigma_i\sqrt{a_i}} K_i \tag{2}$$

Where σ_{j+1} is the current loading stress; σ_i is the loading stress at step *i* (when FE crack modeling created); a_j is the total crack length after loading stress σ_j ; a_0 is total crack length at step *i*; K_i is stress intensity factor at step *i*. This algorithm can quickly calculate the stress intensity factor at random loading stress, and reduce the crack length calculation.
Considering the effect of I-II mixed type stress intensity factors on the growth rate of multiple cracks, we propose the following crack growth model to predict WFD life:

$$\frac{da}{dN} = ce^{\beta(\frac{2}{\pi}\arctan\left|\frac{K_I}{K_{II}}\right|-1)}\left(\Delta K_{eq}\right)^n \tag{3}$$

Where ΔK_{eq} is the effective stress intensity factor, $\Delta K_{eq} = \sqrt[0.25]{\Delta K_I^4 + 8(\Delta K_{II})^4}$; C,n,β are material parameters; K_I, K_{II} are respectively I-type and II-type stress intensity factors. This crack growth model has been verified by CT model test.
If the crack growth length and crack path direction at step *i* are respectively Δa and θ_c, the new crack tip location at step *i+1*,written as ($x_{i+1,-1}, y_{i+1,-1}$) in Cartesian coordinate system, can be obtained as following:

For the cracks in plane:

$$\begin{cases} x_{i+1,-1} = x_{i,-1} + sign(x_{i,-1} - x_{i,-2})\Delta a\cos\theta_c \\ y_{i+1,-1} = y_{i,-1} + sign(x_{i,-1} - x_{i,-2})\Delta a\sin\theta_c \end{cases} \tag{4}$$

For the cracks in curve (described in *Figure 1*):

$$
\begin{cases}
x_{i+1,-1} = x_{i,-1} + sign(x_{i,-1} - x_{i,-2})\Delta a \cos\theta_c \cos(\dfrac{\Delta a \cos\theta_c}{R}) \\
y_{i+1,-1} = \sqrt{R^2 - x_{i+1,-1}^2} - R\cos(\dfrac{\mathrm{L}}{R}) \\
z_{i+1,-1} = z_{i,-1} + sign(x_{i,-1} - x_{i,-2})\Delta a \sin\theta_c
\end{cases}
\tag{5}
$$

Where $x_{i,-1}, y_{i,-1}$ are the coordinates of crack tip at step i; $x_{i,-2}$ is the coordinate of the point with the minimum distance with crack tip; L is half arc length of fuselage curve panel.

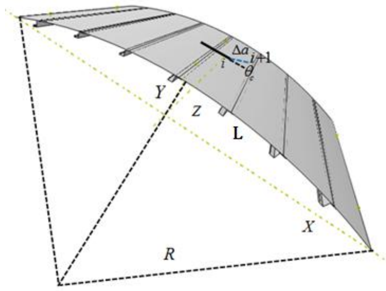
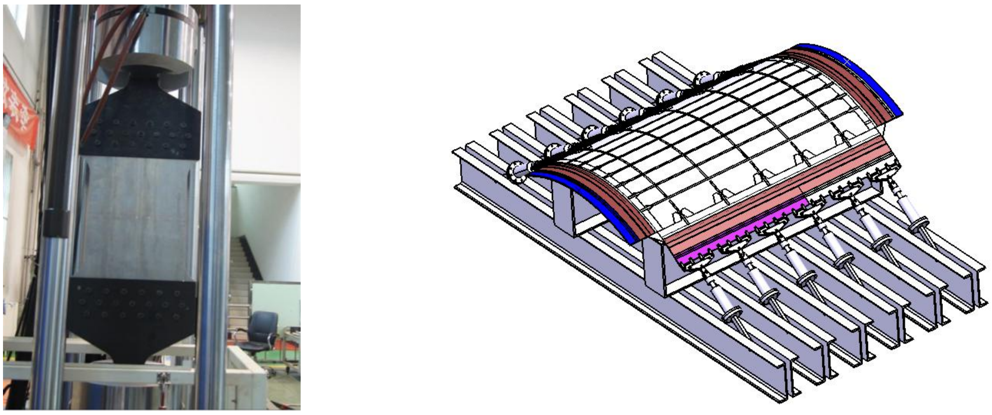


Figure 1. Description of crack coordinates in curved panel

The plane with WFD and the curved panel with two cracks are also analyzed by test to verify the modeling. The testing details are described in Figure 2. The test rig has been proposed to realize the internal pressure loading for curved panel. It can well simulate the pressure load with uniform distribution. The circular load owning to boundary limitation can also be eliminated in the process of increasing pressure load. The test rig gives a good support for the design of new type civil aircraft. The test result shows that the average stress value in the key area is 66.1Mpa when the inner pressure load arrives at 54980Pa, while the error estimation between test and the prediction by engineering method is only 0.1%.



a) Test rig of the plane with WFD b) Curved panel subjected to inner pressure loading

Figure 2. Test rig in horizontal type

Compared with crack growth path and life, the numerical simulations by FEM model have a good agreement with the test results. For the plane with WFD, The average test result of crack propagation life is 245542 cycles, and the numerical result is 263885 cycles; For the curved panel with two cracks, the test result is 97000 cycles and the numerical one is 95038 cycles. In view of engineering application, the analytical model can give a good prediction for the aircraft panels with multi-cracks.

Additionally, our modeling also works well for the WFD evaluation of structures with inclined multiple cracks, Further details will be described in the full article.

Keywords: stress intensity factor, multiple cracks, crack growth models, Widespread Fatigue damages