ESTIMATION OF CRACK TURN PHENOMENON

A. V. Berezin*, A. V. Kulemin, B. G. Nesterenko*, G. I. Nesterenko****
*** Institute Mechanical Engineering Russian Academy of Sciences (IMASH RAS), Russia**
**** Central aerohydrodynamic institute (TsAGI), Russia**

Keywords: *double cantilever beam, cruciform specimens*

Abstract

Experimental data are presented resulted from testing double cantilever beam and cruciform specimens. Double cantilever beam tests resulted in the estimate of the effects on the crack growth of the following factors: initial notch length, material orthotropy, loading type (static/fatigue). The effects of crack arrester thickness and biaxiality factor have been estimated for cruciform specimens. The comparison is given of experiments and calculations based on linear fracture mechanics.

1 Second order theory of crack turn

A series of theories has been outlined to describe crack turn. Recently many authors are in favour of the assumption that second order theory is in the best compliance with experimental data [1].

According to this theory the crack propagates in the direction of maximum shearing (tangential) stress at the crack tip. Based on this theory a second order equation (1) is outlined wherefrom momentary angle of crack growth $\Delta\theta_c$ is determined

$$\frac{K_{II}}{K_I} = \frac{-2\sin\frac{\Delta\theta_c}{2}}{(3\cos\Delta\theta_c - 1)}\left[\cos\frac{\Delta\theta_c}{2} - \frac{8T}{3K_I}\sqrt{2\pi r_c}\cos\Delta\theta_c\right] \quad (1)$$

where K_I and K_{II} – stress intensity factors of forms I and II, T – crack side stress parallel to it, r_c - material property (for alloys 2024-T3 r_c = 1.27÷1.524mm [1]).

The crack tends to turn $\Delta\theta_c>0$ only if inequality is satisfied

$$r_c > r_0 = \frac{9}{128\pi}\left(\frac{K_I}{T}\right)^2 \quad (2)$$

where r_0 – distance forward from the crack tip where the angle of maximum tangential stress becomes different from zero.

Many materials like metals affected by pressure are practically isotropic and elastic, but they tend to dominating direction in crack propagation due to material treatment method. With regard for material orthotropy the theory authors have transformed eq.(1) into the form:

$$\frac{K_{II}}{K_I} = \frac{\sqrt{\frac{r_c}{r_0}}\sin\left(\frac{\Delta\theta_c}{2}\right)(2\cos\Delta\theta_c - \psi\sin\Delta\theta_c) - \sin\Delta\theta_c - \frac{2}{3}\psi(1+\cos\Delta\theta_c)}{3\cos\Delta\theta_c - 1 - 2\psi\sin\Delta\theta_c} \quad (3)$$

$$\psi = \frac{(\bar{K}_m^2 - 1/\bar{K}_m^2 + 1)\sin 2(\theta + \Delta\theta_c)}{1 + (\bar{K}_m^2 - 1/\bar{K}_m^2 + 1)\cos 2(\theta + \Delta\theta_c)}$$

where $\bar{K}_m$- coefficient of fracture orthotropy defined by the relation of maximum loads sustained by the specimens with identical notch lengths, but different material rollings. Parameter θ for LT coupons is 90º while it is equal to 0º for TL coupons [1].

Therefore, in accordance with second order theory of crack turn the calculation of crack growth path requires calculation of the following parameters: K_I, K_{II} and T - crack tip stress. These parameters are found using finite element method.

2 Results of the experiment

TsAGI has conducted comprehensive experiments on double cantilever beams (DCB) and cruciform specimens (Fig.1) to justify second order theory of crack turn and to develop some alternative theory.

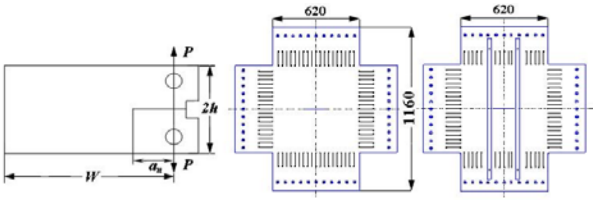

Fig. 1. View of double cantilever and cruciform specimens

Skin material is presented by 2024-T3 sheets 2 mm thick. Two specimen benches were tested – for static (residual) strength and crack growth rates. Some cruciform specimens had crack stoppers. Stoppers represent two bands. Stoppers are pasted to a surface of a specimen. The specimens had transversal-longitudinal and longitudinal-transversal material fiber orientation. Principal results of static tests are presented in Table 1.

Table 1. Residual strength test result for DCB specimens

№	Initial crack a_i (mm)	$r_0(a_i)$ (mm)	Max load P (kgf)
02-LT	92	1.854	621
04-LT	42	5.216	1021
06-LT	142	1.329	412
12-TL	92	1.853	609
14-TL	42	5.168	1005
16-TL	142	1.324	408

Photos some tested is cruciform specimens are presented in Fig.2.

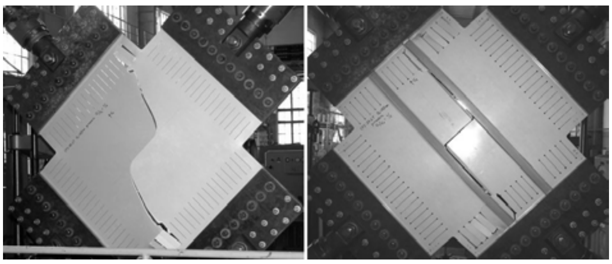

Fig. 2. Photos some tested is cruciform specimens

In the course of fatigue strength testing cruciform specimens the following effect has been observed of biaxiallity value λ (factor λ is equal to the ratio of stress perpendicular to the notch σ_1 to that parallel to the notch σ_2) and stiffening value μ (factor μ presents the increment of specimen cross section due to crack stoppers) on the crack turn:

1. Unstiffened specimens having crack length $2a$=250mm demonstrate sharp crack turn at biaxiallity factor $\lambda=\sigma_1/\sigma_2=1/2$. Slight crack turn is observed at λ=1/1.5. Sharper crack turn happens in unstiffened specimens having crack length $2a$=150mm at λ=1/1.5 than it takes place in the unstiffened specimen having crack length $2a$=250mm at the same value of λ.
2. There happens a sharp crack turn near the bonded straps in the unstiffened specimens having crack length $2a$=150mm at λ=1/1.5; λ=1/2; μ=0.3; μ=0.4.

The following effect of stress biaxiallity λ of cruciform specimens on their residual strength has been found:

1. Residual strength of unstiffened specimens under biaxial stresses is 1.4 times as large as compared to that for uniaxial stress. Meanwhile fracture load value perpendicular to the notch is practically constant in the range of λ=1/0.5÷1/2.
2. Fracture load parallel to the notch in the stiffened specimens is practically constant for λ=1/1.5÷1/2.

3 Verification of second order theory

Test-analytical study has been conducted in Ref.[2] of the potential to apply second order theory in describing crack turn. Second order theory was verified only by DCB static testing results.

The values of r_0 presented in the table have been calculated according to the formula:

$$\frac{r_0}{h} = 0{,}0114\left[1 + 0{,}7214\left(\frac{h}{a}\right) + 0{,}2879\left(\frac{h}{a}\right)^2\right]^2 \qquad (4)$$

Formula (4) is valid for DCB specimens having aspect ratio h/W =0.2 and cracks in the range $3 \geq a/h \geq 1$. This formula has been analytically outlined by the authors of Ref.[3].

To bring the resultant experimental data into compliance with second order theory Ref.[2] gives the estimate of relation between K_{II}/K_I and crack length a. It was also assumed that the relation K_{II}/K_I would change in linear manner with increasing crack length a at the stage of crack turn in DCB specimens. The relation K_{II}/K_I was given in the form:

$$(K_{II}/K_I)_j = \varphi\ (a_i - a_j) \quad (5)$$

where a_i – initial crack length, a_j – current value of crack length, φ – dimensionless factor.

The algorithm to outline relation (5) is as follows:

1. Experimental crack path was divided into segments $\Delta a = r_c$ (it is assumed r_c=1.3 mm).
2. Angle increment $(\Delta\theta_c)_j$ was measured for each segment increment.
3. The values of relation $(K_{II}/K_I)_j$ were calculated by eq.(3) for each crack growth increment Δa. Parameter $(r_0)_j$ was found for each increment by eq.(4). Coefficient of fracture orthotropy was K_m=1.02.
4. Empiric relation of changing ratio K_{II}/K_I in the process of crack growth is a result. This relationship for most DCB specimens turned out to be a straight line. Hence a factor φ = 0.0015 was outlined.

Crack paths for DCB specimens based on the simplified eq.(5) are shown in Fig.3. Therefore, crack turn in DCB specimens under static loading may be described by second order theory.

It should be noted that the suggested eq.(5) is valid for 2024-T3 sheets (fuselage), for DCB specimens having a definite geometry (h/W=0,2 и $3 \geq a/h \geq 1$.).

There is no up to now analytical relation like eq.(4) for cruciform specimens. To determine r_0 in cruciform specimens complicated calculations should be carried out using finite element method.

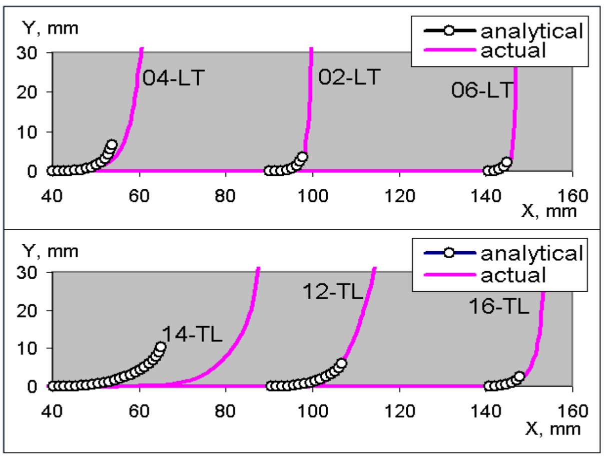

Fig. 3. Comparison of experimental and analytical crack paths

4 Alternative theory

Refs.[4] and [5] have analyzed the potential of applying second order theory in crack turn and some alternative theory for crack turn description is suggested.

To get that effect special software has been developed BASIL_TAN and BASIL_INT to analyze crack turn in DCB and cruciform specimens. This software computes crack turn in isotropic material using finite element method.

Software BASIL_TAN is based on the assumption that the crack would grow in the direction of maximum shearing (tangential) stress, and it computes K_I , K_{II} and T stresses using finite element method to define turn path.

Software BASIL_ INT is based on the assumption that the crack would grow in the direction of maximum ratio σ_0/σ_i , where σ_0 – spherical part of stress tensor, σ_i – stress intensity, and it computes K_I , K_{II} using finite element method to define turn path.

On the basis of calculations and their comparison with TsAGI experimental results the authors have come to the following conclusions:

1. The drawback of the algorithm based on T-stresses is the difficulty in their single-value definition. On one hand, to get maximum accuracy the stresses should be found in the location being the closest to the crack tip. On the other hand, singularity effect results here in large errors. Due to this contradiction in the available recommendations for T –stress definitions proper strictness is lacking that results in their probable inaccurate definition. This, in turn, affects the accuracy of key parameter being in quadratic dependence of T –stresses.
2. It is obvious in the experiments that there are some relations between crack growth direction and stress state type. The stress state type characteristic for plain stress state is the ratio σ_0/σ_i. This ratio defines the growth of microflaws in the process of metal plastic strain occurring at the crack tip and causes its propagation. It enables to judge the biaxiality degree of the stress state in the body with a crack. Therefore one crack growth criteria may

be σ_0/σ_i ratio taken at the crack tip. Maximum value is outlined from the relation $\partial(\sigma_0/\sigma_i.)/\partial\theta$, and the value $\theta=\theta_c$ defines crack turn angle. The substantiation of the above alternative theory is the comparison of analytical and experimental data both for cruciform specimens (Fig.4) and DCB specimens (Fig.5). Experimental data are taken from the specimen fatigue tests.

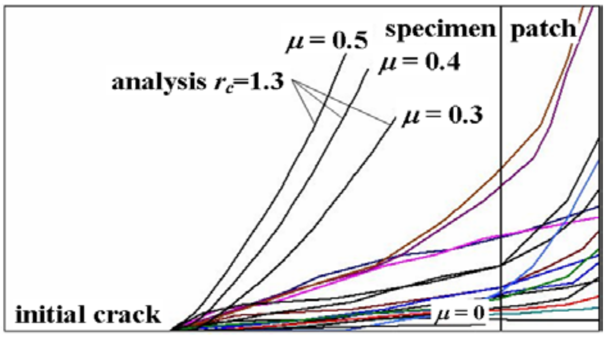

Fig. 4. Comparison of experimental and analytical crack paths in cruciform specimens

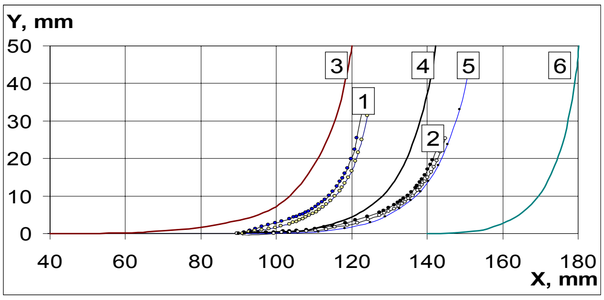

Fig. 5. Comparison of experimental and analytical crack paths in DCB specimens: 1- test fatigue, *a*=90, LT; 2- test fatigue, *a*=90, TL; 3- analysis, *a*=40, r_c=1.3; 4- analysis, *a*=90, r_c=1.3; 5- analysis, *a*=90, r_c=0.6; 6- analysis, *a*=140, r_c=1.3

It follows from the comparison of these data that experimental and analytical results are in satisfactory agreement in TL direction in terms of crack growth, while LT direction demonstrates the difference between analysis and experiment in 4 times for the specimens without crack arresters. Analytical model gives proper representation of arrester effects on the crack path.

To take into account the effect of different resistivity (under tension and compression) and non-linearity in the direction of crack propagation the relationships are required between crack resistance parameters and 2024-T3 anisotropy and resistivity difference

It should be noted that fracture mechanics for anisotropic body has been developed in the smaller degree than that for isotropic one.

Crack turn phenomenon in the structural materials belongs to non-linear fracture mechanics. The following is required for adequate analytical description of this phenomenon:

– establishing state equations for the material under study and establishing its symmetry in linear and non-linear segment of its behaviour;

– developing non-linear fracture mechanics for the material under study with regard for its strain and structural features;

– establishing crack propagation criterion in the material under study by experiments using fracture surface fractograms;

– developing software for numerical treatment of experimental results for the specimens and full-scale structures

References

[1] Pettit R. G., Wang J. J., and Toh. C. *Validated Feasibility Study of Integrally Stiffened Metallic Fuselage Panels for Reducing Manufacturing Costs.* The Boeing Company, Long Beach, California NASA/CR-2000-209342 May 2000.

[2] Kulemin A.V. *Assessment of methods for crack turn analysis*. Trudy TsAGI №2675, 2007 (in Russian).

[3] Leevers P.S., and Radon J.C., *Int. J. of Fracture*, Vol.,19, pp. 311-325, 1982.

[4] Berezin A.V., Zhirkevitch B.Yu., Schmidt H.-Ju. *Crack turn in metallic materials*. “Problems of Mechanical Engineering and automation”, 2003, №3, p.6-12 (in Russian).

[5] Berezin A.V.,Vishnyakov A.V., Zhirkevitch V.Yu., Nesterenko B.G., Nesterenko G.I. *Simulation of marcocrack turn in 2024-T3 Al-alloy*. Linearity and non-linearity. Proceedings of International Scientific Symposium, Moscow Jan. 19-20, 2006 (in Russian).

Copyright Statement