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INVESTIGATION OF BULGING EFFECTS ON PROPAGATION OF 1-BAY AND 2-BAY LONGITUDINAL CRACKS WITH BROKEN/INTACT STIFFENER

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Abstract

Incorrect modeling of bulging of fuselage skin due to internal pressure can lead to significant mistakes in predictions of fatigue crack growth. Comparison of the basic bulging models shows that using models of Swift and of Chen &Schijve in calculations gives the best agreement with experimental data. For these models new technique of calculation of duration of 2-bay longitudinal crack with broken stiffener was suggested. Comparison of calculated crack growth duration (2-bay, broken stiffener) and experimental data demonstrate excellent agreement. It was shown that influence of biaxial loading on bulging effects is significant.

1 Introduction

Longitudinal cracks offer problems in investigations of fatigue crack growth because they occur in a curved thin sheet structure under biaxial loading conditions and internal pressure. The fatigue crack edges bulge outwards (out-of-plane deformation) (Fig. 1) which considerably complicates the fracture mechanics analysis.

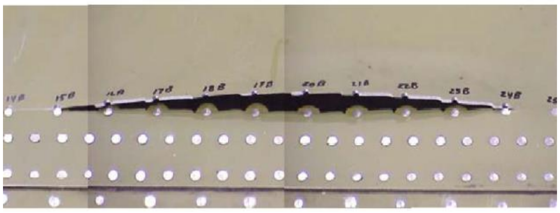

Fig.1. The fatigue crack edge bulges outwards

It was evident from visual observation that bulging out of the crack edges was substantially reduced under the biaxial conditions.

The application of fracture mechanics on fatigue cracks becomes problematic when crack edge bulging occurs. As a part of present study a bulge factor has been adopted, defined by:

$$\beta = \frac{K_{curved}}{K_{flat}}, \qquad (1)$$

The stress intensity factor K_{curved} applies to the pressurized fuselage where bulging occurs. K_{flat} applies to a flat sheet specimen (panel) of the same material and thickness, and similar geometrical conditions.

2 Comparison of Bulging Models

2.1 Bulging models

At present day there are more than 10 different bulging models. In this paper to verify the most important bulging models (swift (2) [1]; Brooke (Jeong and Tong) (3) [2]; Bakuckas (4) [3]; Rose, a young and Starnes (5) [4]; Chen and Schijve (6) [5]) experimental data of 1-bay crack fatigue growth in the fuselage skin of the aircraft Yak-42 were used.

$$\beta = 1 + \frac{10a}{R} \qquad (2)$$

$$\beta = \sqrt{1 + \zeta\left[\left(\frac{E}{\sigma_{hoop}}\right)\left(\frac{a}{R}\right)^2\right]^{2/3}} \qquad (3)$$

$$\beta = 1 + 0.775\left(\frac{E}{\sigma_{hoop}}\right)^{1/3}\left(\frac{a}{R}\right)^{5/6} \qquad (4)$$

$$\beta = \min\left(\beta_{lin};\beta_{nl}\right) \quad (5)$$

$$\eta = \sqrt{\frac{\sigma_{hoop}}{E}\frac{R}{t}}\sqrt[4]{12\left(1-\nu^2\right)}$$

$$\lambda = \frac{a}{\sqrt{Rt}}\sqrt[4]{12\left(1-\nu^2\right)}$$

$$\beta_{lin}^2 = 1+0.5\lambda^{1.725}$$

$$\beta_{nl}^2 = 1+\left(0.15+1.75e^{-0.8\chi}\right)\left(\frac{\lambda}{\eta}\right)^{1.4-0.52e^{-0.43\chi}}$$

$$\beta = \sqrt{1+M} \quad (6)$$

$$M = \frac{5}{3\pi}\frac{Eta}{R^2P}\frac{0.316}{\sqrt{1+18\chi}}\tanh\left[0.06\left(\frac{R}{t}\right)\sqrt{\frac{Pa}{Et}}\right]$$

where a – half crack length; R – fuselage radius; E – skin elastic modulus; t – skin thickness; P – internal pressure; χ – stress biaxility ratio ($\sigma_{long}/\sigma_{hoop}$); σ_{long} and σ_{hoop} – longitudinal and hoop stresses.

There are two types of equations:

1) $\beta = 1+M_i$ – equations (2) and (4);
2) $\beta = \sqrt{1+M_i}$ – equations (3), (5) and (6).

Equations (2-6) were developed for the unstiffened cylinder. Therefore to cover the effect of fuselage frames these equations were modified by introduction two “damping” factors proposed in the literature. For 1-bay crack “damping” factors are defined as follows:

$$X = \cos\left(\frac{\pi a}{b}\right)+F\left\{1-\cos\left(\frac{\pi a}{b}\right)\right\} \quad (7)$$

$$D = \frac{1+\cos(2\pi a/b)}{2}+F\frac{1-\cos(2\pi a/b)}{2} \quad (8)$$

where b – stiffener spacing; F – damping factor.

Using “damping” factors X and D bulge factor for 1-bay longitudinal crack is modified as follows (Fig. 2):

1) $\beta = 1+M_iX$ – equations (2) and (4);
2) $\beta = \sqrt{1+M_iD}$ – equations (3),(5) and (6).

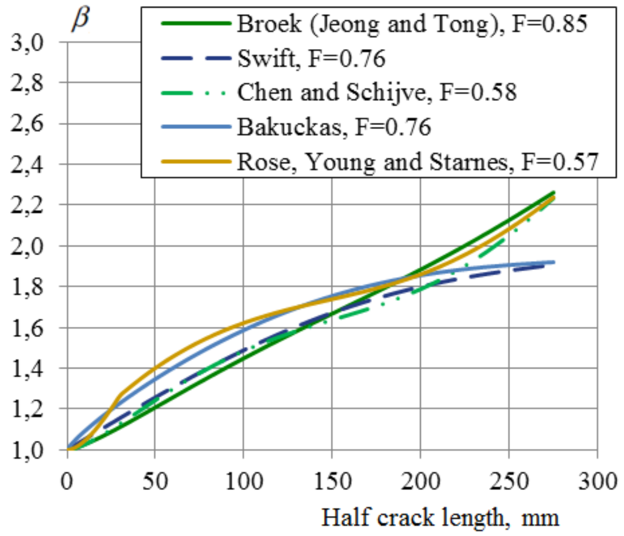

Fig. 2. Bulge factor for 1-bay longitudinal crack

2.2 Initial data and Methodology

To compare bulging models considered above (Fig. 2) experimental data of growth of 1-bay longitudinal crack in the fuselage skin of the aircraft Yak-42 were used. Test results of fuselage of the Yak-42 carried out in TsAGI.

Material of fuselage skin and frames (stiffener) is made by using D16AT sheet 1.2 mm. Frames immediately attached to fuselage skin.

Geometrical characteristic of Yak-42 fuselage (Fig. 3): R = 1900 mm, b = 400 mm, t = 1.2 mm, P = 0.5 ATM, χ = 0.5.

Fig. 3. The aircraft Jak-42

In calculations of crack growth rate and duration were used the following equations: relationship between internal pressure, fuselage radius and thickness and hoop stresses (7), stress intensity factor K_{curved} (8) and equation of crack growth rate (9).

$$\sigma_{hoop} = \frac{P \cdot R}{t} \quad (9)$$

$$K_{curved} = \beta \cdot K_{flat} = \beta \cdot \sigma_{hoop} \sqrt{\pi \cdot a} \cdot \varphi \quad (10)$$

$$\frac{da}{dN} = C \frac{\Delta K^m}{(1-R)K_c - \Delta K} = C \frac{K^m_{curved}}{K_c - K_{curved}}, \quad (11)$$

where for D16AT sheet 1.2 mm: $C = 1.261 \cdot 10^{-7}$, m = 3.397, K_c = 342 kgf/mm$^{3/2}$;
φ – correction factor considered geometrical features of stiffened construction.

2.3 Results of comparison

- Models of Rose, Young & Starnes and Chen & Schijve take into account biaxial loading; model Chen & Schijve also takes into account effect of internal pressure in fuselage.
- Model of Bakuckas doesn't take into account biaxial loading and internal pressure in fuselage.
- Calculations of crack growth duration show that using bulging models for unstiffened cylinder and for 1-bay stiffened fuselage lead nearly to the same results. It's explained by slight influence of stiffeners on bulging effects.
- Using model of Rose, Young & Starnes gives underestimated results in comparison with experimental data (Fig. 4).
- On Figure 4 is represented calculation without bulging effects that shows significant influence of bulging on crack growth duration.
- Using models of Swift and of Chen and Schijve gives the best agreement with experimental data (Fig. 4). These models were used in the consequent investigations of bulging effects on propagation of 2-bay longitudinal cracks in pressurized fuselage.

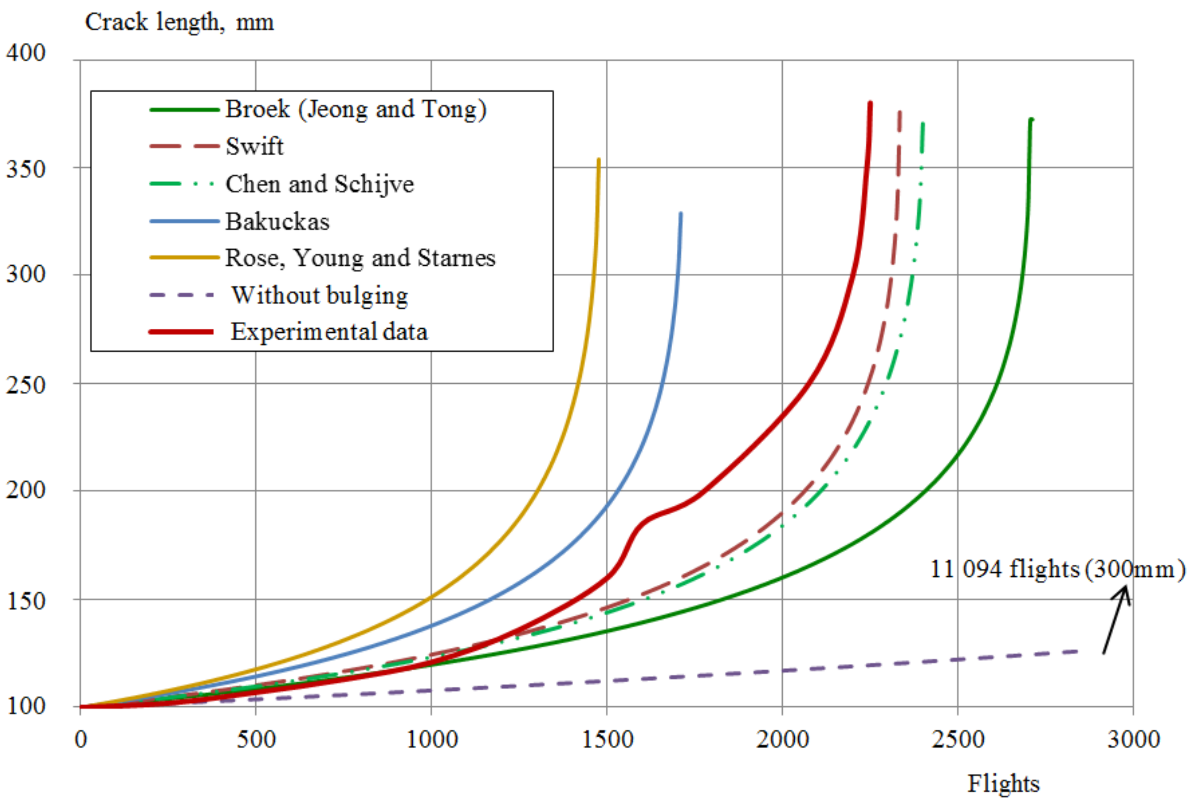

Fig. 4. Comparison of calculation results of crack growth duration (1-bay) and experimental data

3 Investigations of bulging effects on propagation of 2-bay longitudinal crack with broken/intact stiffener

3.1 Bulging models of Swift and Chen & Schijve

Models of Swift and of Chen & Schijve were investigated for unstiffened cylinder, for 1-bay crack in stiffened fuselage and for 2-bay crack with intact stiffener. These models for 2-bay crack with broken stiffener were suggested by NASGRO's team however weren't verified by using experimental data.

For 2-bay longitudinal crack with intact stiffener models of Swift and of Chen & Schijve are defined by Eq. 12, 13 and Eq. 14, 15 respectively.

$$\beta = 1 + 5\left(\frac{b/2}{R}\right)\cdot X \qquad (12)$$

$$X = \frac{1+\cos(2\pi x/b)}{2} + F\,\frac{1-\cos(2\pi x/b)}{2}, \qquad (13)$$

where $x = a - b/2$

$$\beta = \sqrt{1+MD} \qquad (14)$$

$$D = \frac{1-\cos(2\pi a/b)}{2} + F\,\frac{1+\cos(2\pi a/b)}{2} \qquad (15)$$

$$M = \frac{5}{12\pi}\frac{Etb}{R^2P}\frac{0.316}{\sqrt{1+18\chi}}\tanh\left[0.06\left(\frac{R}{t}\right)\sqrt{\frac{Pb}{4Et}}\right]$$

These equations (12-15) model bulging that occurs in pressurized fuselage and schematically represented in Figure 5.

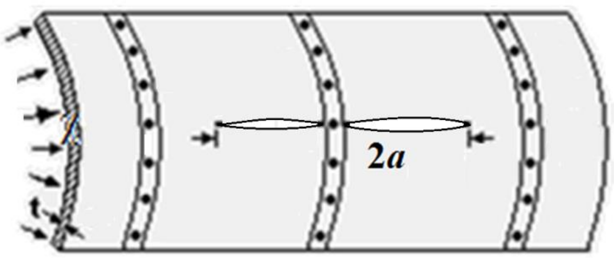

Fig. 5. Bulging of fuselage skin with 2-bay longitudinal crack with intact stiffener

For 2-bay longitudinal crack with broken stiffener models of Swift and of Chen & Schijve were suggested by NASGRO's team and are defined by Eq. 16, 17 and Eq. 18, 19 respectively.

$$\beta = 1 + 5\left(\frac{2a}{R}\right)\cdot X \qquad (16)$$

$$X = \cos\left(\frac{\pi a}{2b}\right) + F\left\{1-\cos\left(\frac{\pi a}{2b}\right)\right\} \qquad (17)$$

$$\beta = \sqrt{1+MD} \qquad (18)$$

$$D = \frac{1+\cos(\pi a/b)}{2} + F\,\frac{1-\cos(\pi a/b)}{2} \qquad (19)$$

$$M = \frac{5}{3\pi}\frac{Eta}{R^2P}\frac{0.316}{\sqrt{1+18\chi}}\tanh\left[0.06\left(\frac{R}{t}\right)\sqrt{\frac{Pa}{Et}}\right]$$

These equations (16-19) model bulging that occurs in pressurized fuselage and schematically represented in Figure 6.

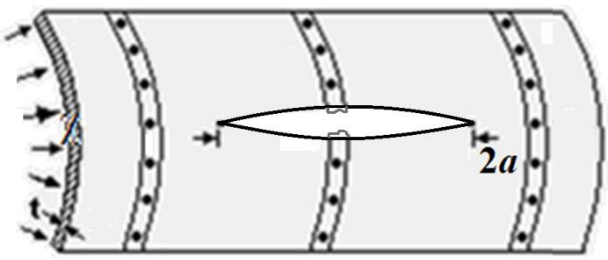

Fig. 6. Bulging of fuselage skin with 2-bay longitudinal crack with broken stiffener

3.2 Calculation of duration of 2-bay longitudinal crack with broken stiffener

By using bulging models of Swift suggested by NASGRO's team calculation of crack growth duration was made.

Experimental data of growth of 2-bay longitudinal crack with broken stiffener in the fuselage skin of the aircraft Yak-42 were used.Test results of fuselage of the Yak-42 carried out in TsAGI.

Initial data and methodology were the same as in p. 2.2 of present paper.

Comparison of experimental data and calculation results of crack growth duration (2-bay, broken stiffener) performed by using NASGRO's bulging model gave difference in 15 times (Fig. 7, curve Swift (NASGRO)). Therefore alter technique was suggested.

In fact broken stiffener retains a residual stiffness in compression, which significantly restricts bulging (Fig. 8). This effect is decreased with increasing crack length and in the presence of a compressive longitudinal stresses. Therefore for calculation of duration of 2-bay crack with broken stiffener was suggested using bulging models for 2-bay crack with intact stiffener (Eq. 12-15). Applying of such philosophy shows excellent agreement of calculation results with experimental data (Fig. 7, curves Swift and Chen & Schijve).

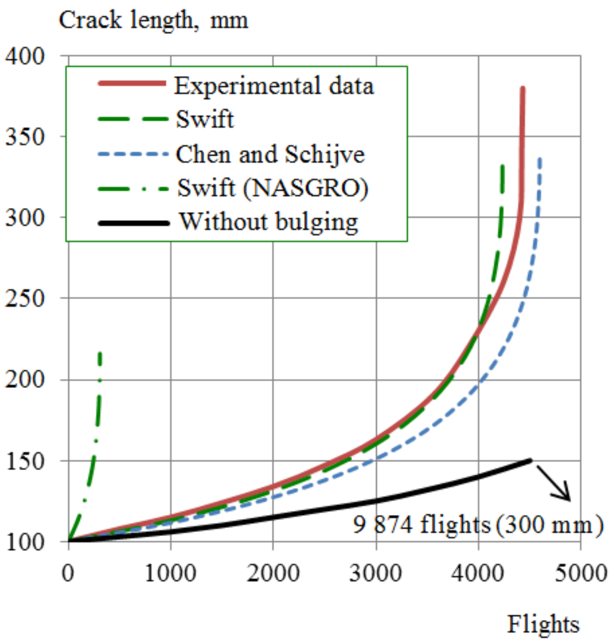

Fig. 7. Comparison of calculation results of crack growth duration (2-bay, broken stiffener) and experimental data

Fig. 8. Bulging of skin in full-scale fuselage with 2-bay longitudinal crack with broken stiffener

Approbation of new technique of calculation of duration of 2-bay crack with broken stiffener is also represented in p. 4 of present paper.

4 Investigations of Influence of biaxial loading on bulging effects (2-bay longitudinal crack with broken stiffener)

4.1 Initial data and Methodology

To demonstrate influence of biaxial loading on bulging experimental data of growth of 2-bay longitudinal crack with broken stiffener in full-scale fuselage panels of medium-range aircraft were used. Test results carried out in TsAGI.

Material of panels skin and frames (stiffener) is made by using 1163RDTV sheet, t = 1.2-1.8 mm. The panels have the following parameters (Fig. 9): R = 2000 mm, b = 550 mm. P = 0.63 ATM, χ = 0.0. There are two types of panels – 6 panels: 905-1, 905-2, 905-3 (first type) and 906-1, 906-2, 906-3 (second type).

As Swift model of bulging doesn't take into account biaxial loading (biaxial ratio, χ) only model of Chen and Schijve was considered in investigations.

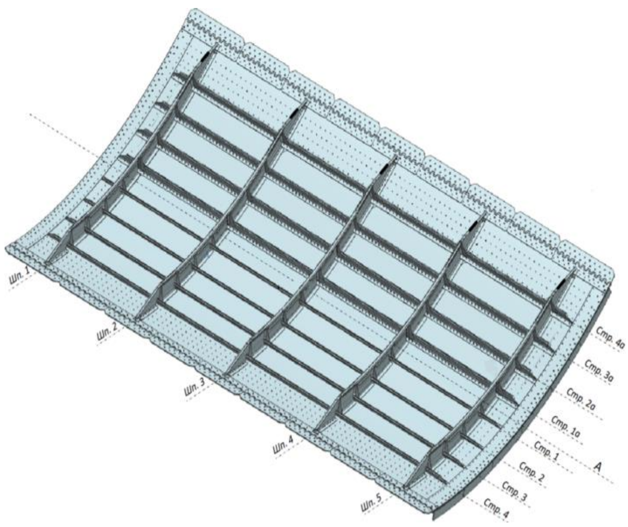

Fig. 9. Schematic view of full-scale fuselage panel of medium-range aircraft

In calculations of crack growth rate and duration were used Eq. 9-11 and Eq. 14-15 and the following material properties: $C = 1.77\cdot10^{-7}$, m = 3.397, K_c = 434 kgf/mm$^{3/2}$.

Calculations of duration of crack growth in full-scale panels were performed for values of biaxial ratio χ = 0.5 и χ = 0. Also calculations without bulging were executed.

4.2 Calculation Results

Results of calculations are represented on Fig. 10-11 in terms of curves “crack growth rate, *da*/*dN* – half crack length, *a* ”.

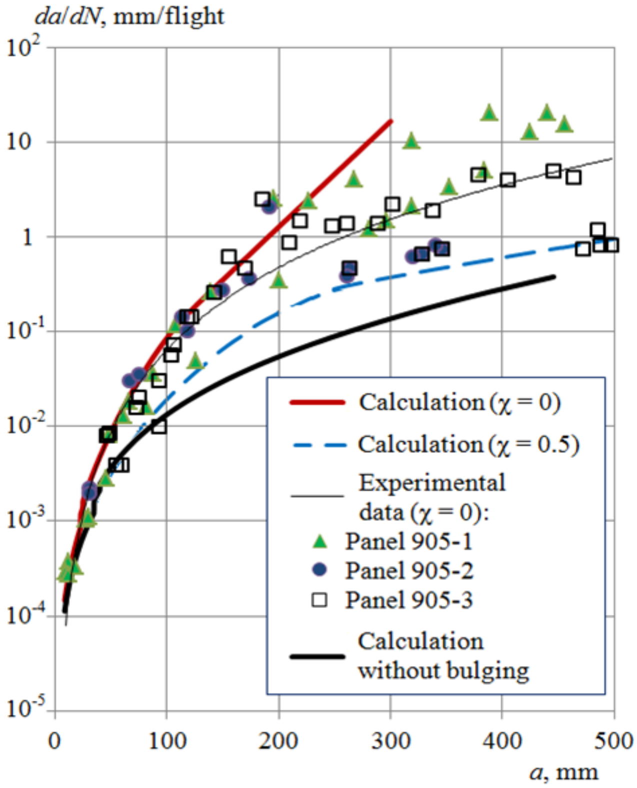

Fig. 10. Calculation results for panels of first type

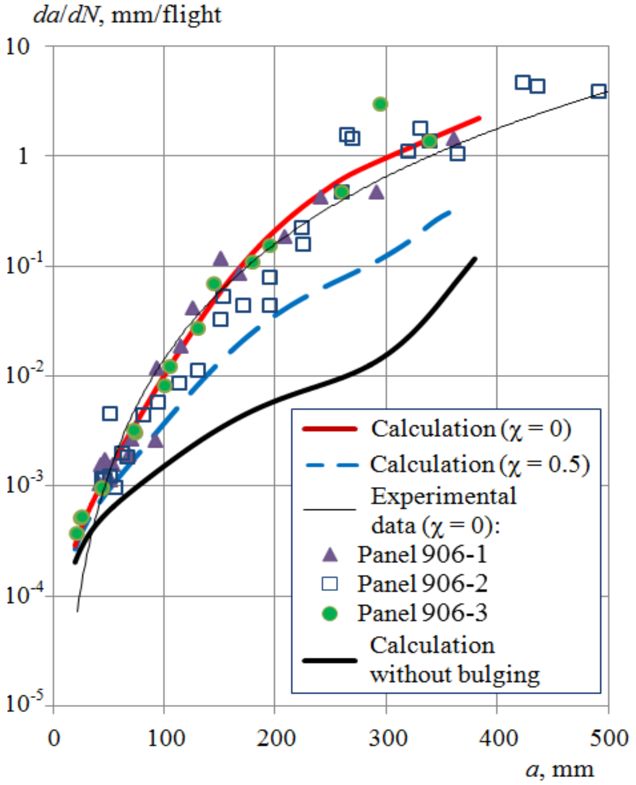

Fig. 11. Calculation results for panels of second type

4.3 Results of Investigations of biaxial loading Influence

Influence of biaxial loading on bulging effects was considered. For this purpose calculations of duration of 2-bay crack with broken stiffener were performed with biaxial ratio of χ = 0.5 и χ = 0. It was shown that using of incorrect value of χ can lead to mistakes in calculations of crack growth rate up to 10 times and in duration up to 3 times.

Conclusions

Comparison of bulging models shows that using models of Swift and of Chen &Schijve gives the best agreement with experimental data. For these models new technique of calculation of duration of 2-bay longitudinal crack with broken stiffener was suggested. Comparison of calculated crack growth duration (2-bay, broken stiffener) and experimental data demonstrate excellent agreement. However Swift model of bulging doesn’t take into account biaxial loading. Influence of biaxial loading on bulging effects was considered. For this purpose calculations of duration of 2-bay crack with broken stiffener were performed with biaxial ratio of χ = 0.5 и χ = 0. It was shown that using of incorrect value of χ can lead to mistakes in calculations of crack growth rate up to 10 times and in duration up to 3 times.

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