ISSN 1330-3651
UDC/UDK [620.191.33:624.073]:519.6

PRACTICAL ASPECTS OF FAIL-SAFE DESIGN – CALCULATION OF FATIGUE LIFE OF CRACKED THIN-WALLED STRUCTURES

Danijela Živojinović, Miodrag Arsić, Aleksandar Sedmak, Snežana Kirin, Radoljub Tomić

Preliminary notes

This paper represents fatigue crack growth life prediction in thin-walled structures (plates or shells). There are two analysis results from two different packages of software: NASGRO and FRANC 3D. They are based on Finite Element Method and Linear Elastic Fracture Mechanics principles (LEMF). Moreover, load interaction to crack growth is analyzed. FRANC 3D software is used to compute and display stress-displacement state of structure and simulation of crack fronts progression. Entire work comprises structural integrity assessment.

Keywords: *number of cycles, fatigue crack growth, fracture, life, stress intensity factor - SIF*

Praktični aspekti konstruiranja sa stajališta sigurnosti – Izračun zamornog vijeka tankostjenih konstrukcija s pukotinom

Prethodno priopćenje

Ovaj članak se bavi predviđanjem životnog vijeka konstrukcija (ploča ili ljuski) obzirom na zamorni rast pukotine. Dobiveni su rezultati dvjema analizama s dva različita softvera: NASGRO i FRANC 3D. Oni se temelje na metodi konačnih elemenata i principima linearno elastične mehanike loma. Dodatno je analizirana interakcija sile i propagacije pukotine. U softveru FRANC 3D su računana i prikazana polja pomaka i naprezanja u konstrukciji, kao i simulacija napredovanja fronte pukotine. Ovaj rad dio je procjene cjelovitosti konstrukcije.

Ključne riječi: *broj ciklusa, zamorni rast pukotine, lom, životni vijek, koeficijent intenzivnosti naprezanja*

1 Introduction

New trends in maintenance of critical aircraft components include decision making process based on risk analysis and 'fail-safe' principle. There are many applied concepts based on risk such as Quantitative Risk Assessment (QRA), Risk-Based Inspection (RBI), Risk-Based Inspection and Maintenance (RBIM), Reliability-Centered Maintenance (RCM) and Risk-Based Life Management (RBLM), [1]. These methods are in an advanced stage of application especially in operation, inspection, maintenance and asset management. National authorities begin to extend inspection intervals for the case that safety is guaranteed in an adequate manner. Risk-based inspection is offering this kind of method; by assessing the risk that includes determination of the probability and consequences of a failure it is possible to define the risk level and consequently to adjust inspection intervals without influencing safety issues.

The RBI methodology enables the assessment of the likelihood and potential consequences of critical aircraft failures; therefore it provides companies with the opportunity to prioritize their equipment for inspection. According to the contribution of the components to the overall risk of the unit, it is possible to determine what components should be inspected for an accepted risk level, [1]. Based on this methodology appropriate inspection program can be established, including optimization of inspection methods, frequencies and resources.

One of the most significant advances in engineering design practice was the change from classical 'safe-life' principle for the components operating in fatigue regime (based on Wöhler's curve) to the 'fail-safe' principle based on crack growth period between the initial and the critical crack length.

This principle enables even the most critical components to be used for prolonged operating time, making significant savings, but not on the expense of safety. Crucial steps in applying the 'fail-safe' principle are precise and conservative evaluation of the initial crack length, of the critical crack length (by applying linear elastic fracture mechanics parameters), and of the crack growth rate, [2-5].

Application of 'fail-safe' principle can be illustrated by the well-known example of jet engine disks [6], where circa 10^9 \$ have been saved in the period of 20 years just by avoiding previously applied replacement procedure.

Recognizing the possibility that cracked components can operate safely under fatigue loading enabled more extensive application of fracture mechanics principles in order to assess their structural integrity. Toward this end, essential data are:

- geometry (shape and dimension, including crack);
- load spectrum;
- fracture toughness, K_{Ic}, for selected material;
- initial and final crack length.

In this paper the fail-safe principle has been applied to thin-walled structures, as typically used in the aircraft industry. The essential part of this procedure is stress-strain analysis of cracked component, which should be as precise as possible. Having this in mind, the Finite Element Method (FEM) has been applied here, as the most convenient numerical method for problems with complex geometry, such as cracked thin-walled components. As the most appropriate for cracked thin-walled structures, the software packages NASGRO, [7] and FRANC 3D, [8, 9], have been used. Both of them are based on the fracture mechanics principles and are capable of calculating the critical crack length and number of cycles until fracture for a component under known load spectrum. The basic aim of using two software packages was to make comparative analysis of results.

2 Software NASGRO

Software NASGRO is used for the calculation of components life under fatigue load. This software is developed by NASA (National Aeronautics and Space Administration) with the purpose to obtain valid data and resolve problems related to critical component failure. Therefore, special attention is devoted to calculations of crack initiation and crack propagation under dynamic load.

NASGRO comprises three modules (Fig. 1):

- NASFLA – (1st option) based on fracture mechanics principles, can be used to calculate:
  - fatigue crack growth and life of construction elements (Fig. 2 – 1st option);
  - critical crack sizes – a_{cr} and/or c_{cr} (2nd option);
  - stress intensity factor – K (3rd option);
  - change of crack length in the function of time da/dt (4th option).
- NASBEM – (2nd option) based on the boundary element method for solving complex geometries with or without cracks to obtain:
  - stress intensity factor solution – K
  - stress solution in structure.
- NASMAT – (3rd option) library of material constants used in calculation (crack growth data):
  - material type and specific constants of material;
  - state of material (material condition), applied heat treatment, etc.;
  - crack plane orientation, namely relative position of load direction and crack orientation regard to material fiber;
  - working environment;
  - specimen type with crack type – consists of many different specimen types and crack types (include their position in respect to load direction);
  - initial crack length in materials.

This program assumes that all materials are linearly elastic and homogeneous. All values given in this library are dual, in US Units (in, ksi) and SI Units (mm, MPa) (Fig. 3/Units). A major enhancement to NASFLA is the modeling of crack growth under load interaction.

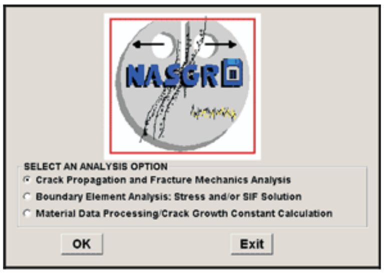

Figure 1 Selection of appropriate module

The most popular module is NASFLA, software for fatigue crack growth calculations and life calculation of structure. It enables the calculation of simple construction, without stiffeners. Following calculations are possible in this module:

I type – **(Direct Life Prediction Analysis)** – direct calculation of crack growth-life versus number of cycles to failure (Fig. 3 - Calculation Type/1st option);

II type – **(Indirect Life Prediction Analysis)** – indirect calculation of initial flaw size, for given life and load spectrum (Fig. 3 - Calculation Type/2nd option);

III type – **(Indirect Life Prediction Analysis)** – indirect calculations of scale factor multiplier (safety factor) and intensity of applied load, for preliminary defined construction that can withstand without fracture, for a given life (Fig. 3 - Calculation Type/3rd option).

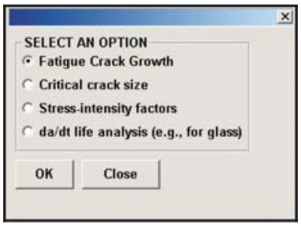

Figure 2 Module options for fracture mechanics calculations

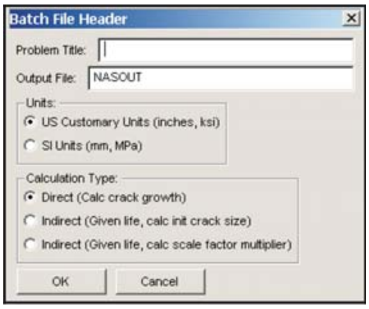

Figure 3 Units and Calculation Type in NASFLA module

For direct calculation of structure (**I type**) the following input parameters are required:

- geometry of construction element and initial flaw size in structure;
- material from preset material library-NASMAT, with all necessary material constants;
- loads or load spectrum (load history);
- working life of construction given as number of applied load cycles;
- display of the parameters results.

Solution of calculation is crack length as a function of number of applied load cycles.

Parameters used in the case of indirect calculation (**II type**) are:

- geometry of construction element and preliminary determined initial flaw size in structure;
- material from preset material library-NASMAT, with all necessary material constants;
- loads or load spectrum (load history);
- working life of construction given as number of applied load cycles;
- display of the parameters results.

For indirect calculation (**III type**), input data are identical with the data from previous calculation. Solution is maximum value for load that construction can withstand for the given number of load cycles. This value is given by scale factor multiplier of load that is defined at the beginning of calculations.

2.1 Examples of direct calculation (I type)

The subject of this article are thin-walled structures. Through crack types TC01 and TC07 have been chosen as the most often used examples of calculation in practice.

Critical stress intensity factor, namely fracture toughness, K_{Ic}, is important material property, which defines material resistance to crack unstable growth.

Practically, K_{Ic} is the minimum value on a diagramme, as shown in Fig. 4, illustrating dependence of the apparent fracture toughness on thickness t, for the mentioned alloys. One can notice that fracture toughness values are decreasing

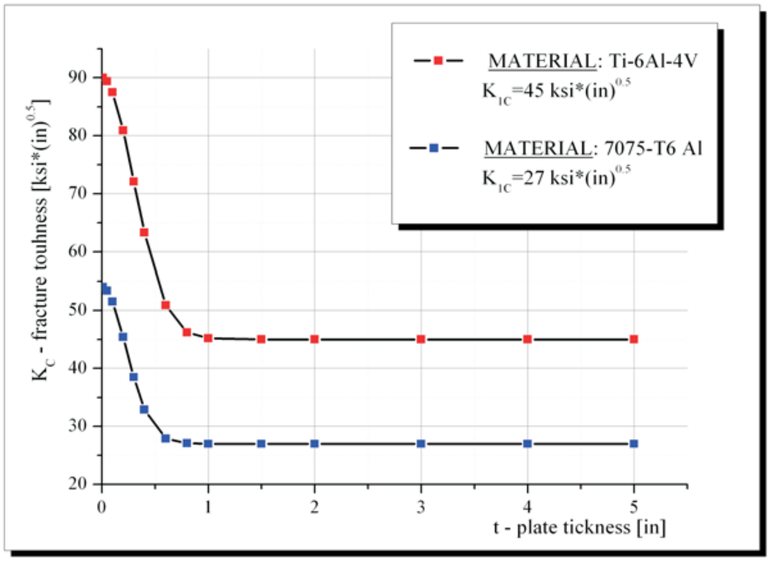

Figure 4 Dependence of fracture toughness K_c on plate thickness t

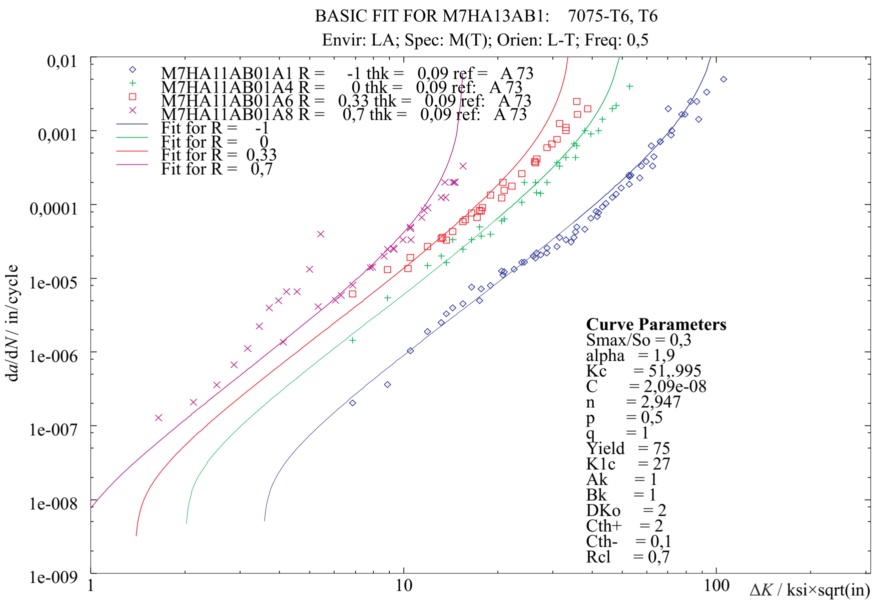

Figure 5 Dependence da/dN on ΔK for aluminum alloy: 7075-T6 Al

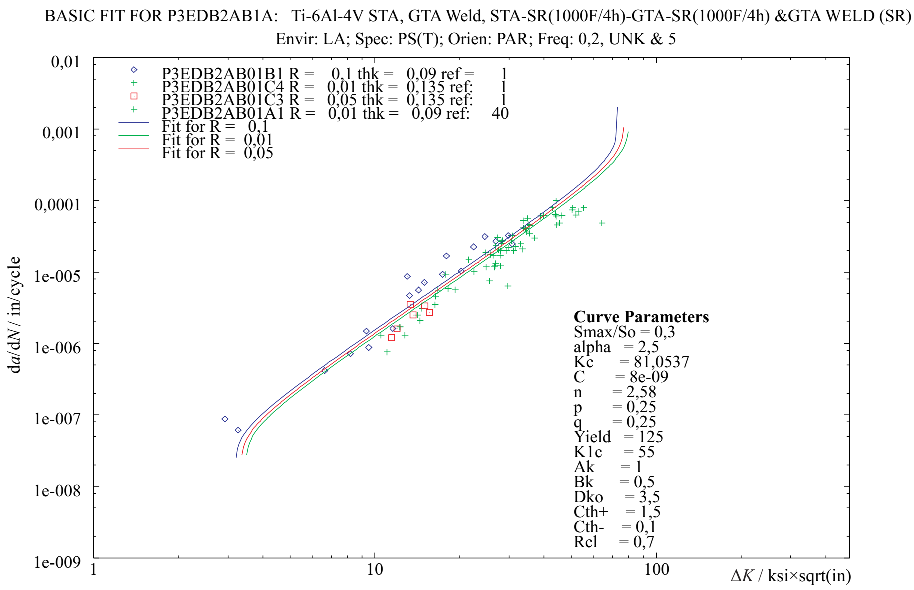

Figure 6 Dependence da/dN on ΔK for titanium alloy: Ti-6Al-4V

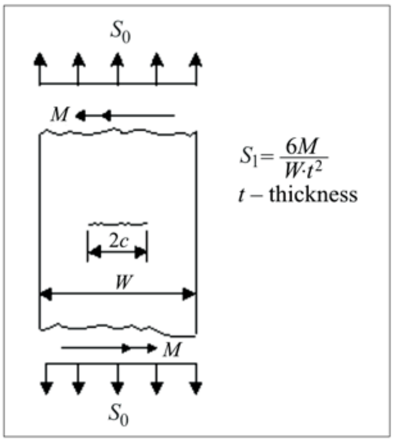

Figure 7 Through crack TC01

with the increase of plate thickness until specific value, the critical fracture toughness, is reached. For two alloys analysed, the first one aluminium alloy 7075-T6 Al,

$$K_{Ic} = 54\ \text{ksi}\sqrt{\text{in}} = 59{,}34\ \text{MPa}\sqrt{\text{m}},$$

and for the second one, titanium alloy Ti-6Al-4V:

$$K_{Ic} = 90\ \text{ksi}\sqrt{\text{in}} = 99\ \text{MPa}\sqrt{\text{m}}.$$

The following relationship has been adopted for through crack, surface crack and standard specimen crack cases, in order to describe fracture toughness – versus thickness behavior for various materials:

$$K_I = K_{Ic}\left(1 + B_K e^{-\left(A_K \frac{t}{t_0}\right)^2}\right) \quad (1)$$

where:
A_K and B_K – material constants

$$t_0 = 2{,}5\left(\frac{K_{Ic}}{\sigma_Y}\right)^2 \quad (2)$$

σ_Y – yield strength.

Crack growth ratio da/dN calculation in NASGRO uses a relationship called the NASGRO equation:

$$\frac{da}{dN} = C\left[\left(-\frac{1-f}{1-R}\right)\Delta K\right]^n \frac{\left(1-\frac{\Delta K_{th}}{\Delta K}\right)^p}{\left(1-\frac{K_{max}}{K_c}\right)^q}, \quad (3)$$

where:
ΔK – stress intensity factor range
C, n, p and q – empirical material constants
f – crack opening function
ΔK_{th} – threshold stress intensity factor.

Figs. 5 and 6 show crack growth data (da/dN – ΔK) for the aluminum alloy 7075-T6 Al and titanium alloy Ti-6Al-4V plotted together with curve fit to previous equation.

2.1.1 Example of through crack – TC01

Specimen type Tc01 – through crack in the middle of plate, is used for the calculation (Fig. 7). Specimen is loaded under tension for the following stress ratios:
$R = 0$ – unilateral stress variation
$R = -1$ – alternate (symmetrical) stress variation
$R = -2$ – alternate stress variation
$R = 0{,}2$ – unilateral stress variation with prestress.

The loading is given as the remote tension:

$$\sigma_{max} = 10\ \text{ksi} = 68{,}95\ \text{MPa}.$$

Specimen dimensions are:
- plate width: $W = 11$ in $= 279{,}4$ mm
- plate thickness: $t = 0{,}1$ in $= 2{,}54$ mm
- initial half-crack length: $c_0 = 0{,}1$ in $= 2{,}54$ mm.

Fig. 8 illustrates the dependency of the half-crack length c, on the number of load cycles N, for the aluminum alloy 7075-T6 Al, whereas Fig. 9 shows the same dependency for the titanium alloy Ti-6Al-4V.

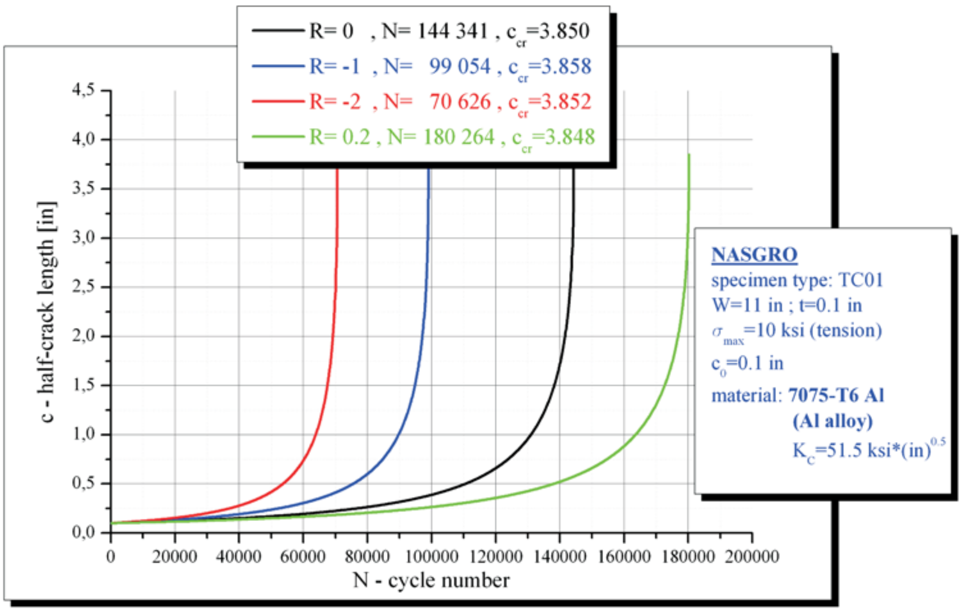

Figure 8 Through crack TC01 – material 7075-T6 Al

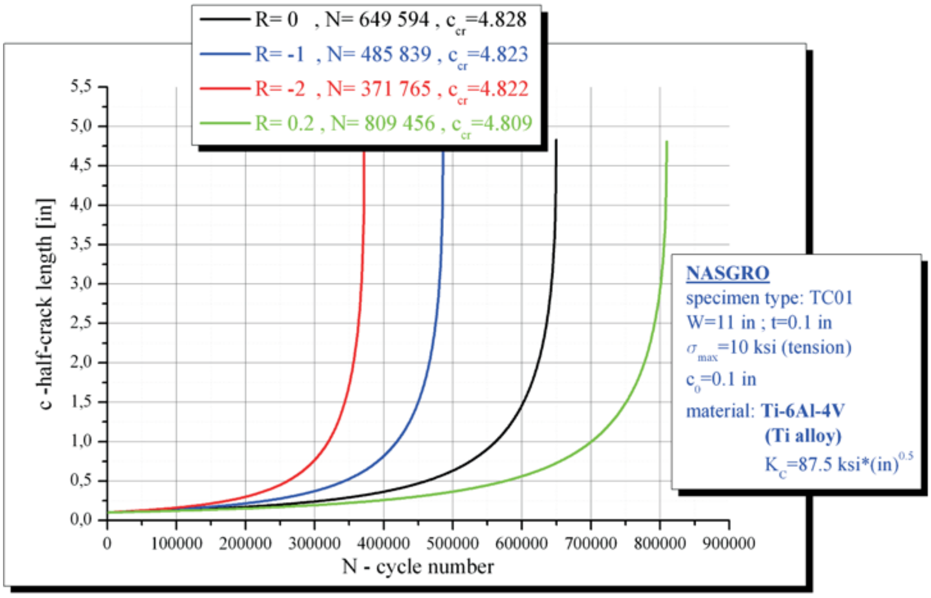

Figure 9 Through crack TC01 – material Ti-6Al-4V

Following conclusions can be derived from previous results:

- Specimen type TC01 can withstand the largest number of load cycles under unilateral stress change with overload (R = 0,2). Rapid increase of number of load cycles that a structure can withstand occurs with the decrease of stress amplitude σ_a, i.e. the increase of stress ratio R. With the increase of stress ratio to value R = 1 conditions of static load in structure are achieved.
- Titanium alloy specimen can withstand larger number of load cycles in comparison with aluminum alloy specimen with the identical geometry and applied load.

2.1.2 Example of through crack – TC07

Specimen in the shape of cylindrical vessel under effect of inner pressure (TC07) is given as an example of through crack calculation (Fig. 10): $p=(0;9)$ psi $=(0;62{,}05)$ kPa.

Effect of inner pressure can be aproximated with adequite tension load, shown with the equation:

$$\sigma = S_0 = \frac{p\cdot R}{t} = \frac{p\cdot(D-t)}{t\cdot 2} \approx \frac{p\cdot D}{t\cdot 2}. \tag{4}$$

Two alloys were analysed: 2024-T3 Al and 7075-T6 Al.

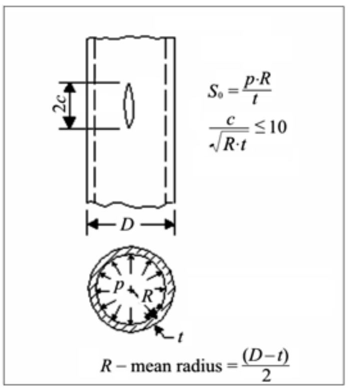

Figure 10 Through crack TC07

Specimen dimensions are:

- vessel diameter: D = 144 in = 3 657,6 mm
- thickness of vessel wall: t = var
- half-crack initial length: c_0 = 1 in = 25,4 mm.

Represented model is the same as the skin of passenger airplane fuselage, where cabin is under cyclic change of pressure (consequence of altitude change and cabin pressurisation). Results are shown in Fig. 11, as a plot of half-crack critical length and number of load cycles.

Half-crack critical length c_{cr} is determined by specimen material and specimen thickness (Tab. 1). For the same material, predicted life of structure is significantly longer for the thicker vessel wall.

While comparing two different alloys, the following was noticed: with the same specimen wall thickness, alloy 2024-T3 Al can undergo a larger number of load cycles in reference to specimen made from alloy 7075-T6 Al. This is the consequence of the fact that the fracture toughness value for material 2024-T3 Al,

$$K_C = 65{,}9\ \text{ksi}\sqrt{\text{in}} = 72{,}41\ \text{MPa}\sqrt{\text{m}}$$

is larger than for the material 7075-T6 Al,

Table 1. Critical crack length c_{cr} and number of cycles to fracture N

Material	Wall thickness	Maximal tension stress	Half-crack critical length	Number of applied fatigue cycles to reach final crack size
	t /in	$\sigma_{max} = S_0$ /ksi	c_{cr} /in	N /–
2024-T3 Al	0,040	16,200	1,822	420
2024-T3 Al	0,051	12,706	2,454	1 942
2024-T3 Al	0,064	10,125	3,201	6 473
7075-T6 Al	0,064	10,125	2,592	3 911
7075-T6 Al	0,081	8,000	3,384	12 062

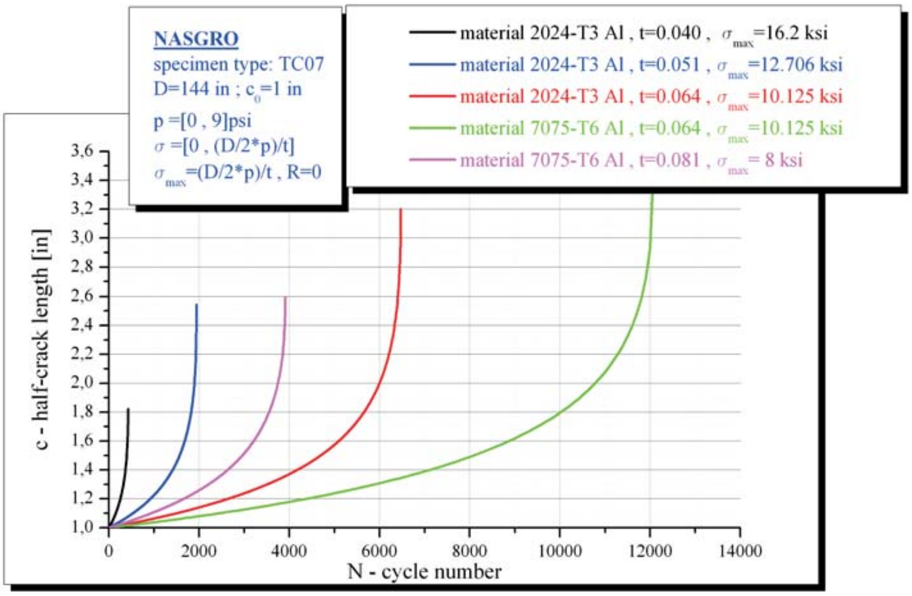

Figure 11 Through crack TC07-pressurized vessel

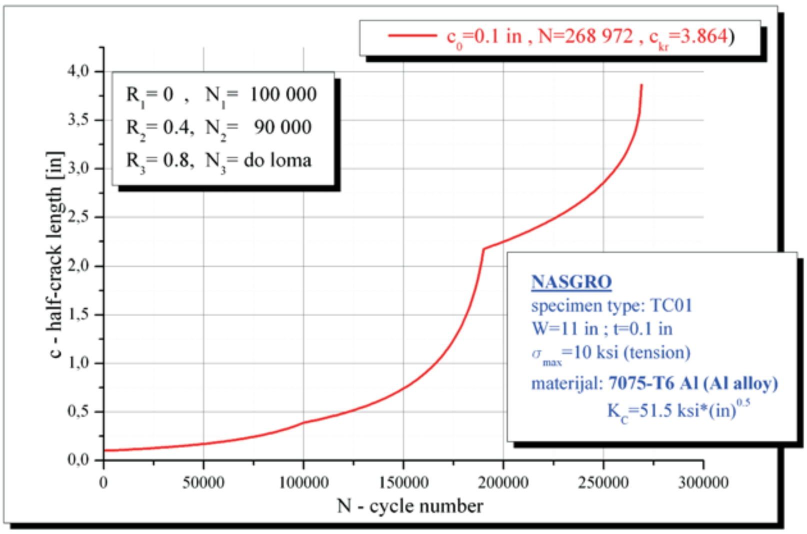

Figure 12 Load interaction at through crack TC01 – material 7075-T6 Al (tension)

2.1.3
Load interaction

In this section, interaction of loads sequence is analyzed. Therefore, there are tests of specimen type TC01 (Figs. 12 and 13) – made from aluminium alloy 7075-T6 Al. Adopted values for both analyses are:

– plate width: $W = 11$ in = 279,4 mm
– plate thickness: $t = 0,1$ in = 2,54 mm
– half-crack initial length: $c_0 = 0,1$ in = 2,54 mm
– maximum stress: $\sigma_{max} = 10$ ksi = 68,95 MPa.

In the first test, the specimen is loaded with combined tension loads:

1) R_1 = 0, unilateral stress variation, with a number of applied fatigue cycles $N_1 = 100\,000$
2) R_2 = 0,4, unilateral stress variation, with a number of applied fatigue cycles $N_2 = 90\,000$
3) R_3 = 0,8, unilateral stress variation, with a number of applied fatigue cycles until fracture of structure.

Fig. 12 illustrates variation of crack growth length c in the function of cycle number of applied load N, with the combination of different stress ratios R.

From Fig. 12 one can notice the decrease of crack growth rate with the change of stress ratio, R. This effect appears if in the first steps unilateral positive load (tension) is applied, followed by the decrease of stress amplitude, σ_a, and the increase of stress ratio, R for σ_{max} = const. Therefore, the decrease of curve gradient $c = f(N)$ for defined material occurs due to the increase of stress ratio (only for certain number of load cycles). The curve afterwards obtains steady slope character.

In addition, the same load interaction at identical specimen is analysed, but under bending load, Fig. 13.

In the case of bending, with the same combination of stress ratios, R_i, and with the same number of load cycles, N_i, for identical specimens, the decrease of crack growth is obvious.

However, the effect of crack growth decrease is more intensive in the case of tension load. In that case, with the same intensity of applied maximum stress, σ_{max}, crack growth is dominant. After the third step of loads R_3 = 0,8 fracture of structure occurs, because critical fracture toughness K_C at the crack tip is achieved. Critical stress intensity factor K_C in bending, is not reached for the same cycle number of load $N = N_1 + N_2 + N_3$. Hence, identical

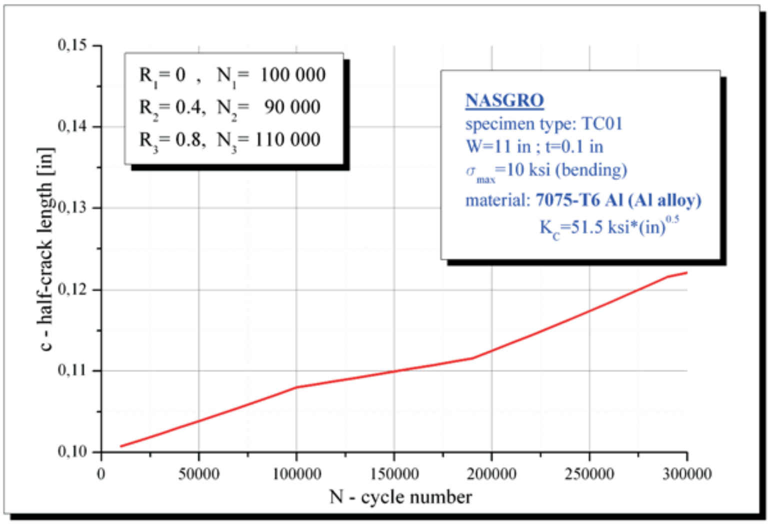

Figure 13 Load interaction at through crack TC01 – material 7075-T6 Al (bending)

specimen under the same combination of stress ratios R_i and the same cycle number of load N_i in the case of bending, can undergo higher cycle number and has longer working life in relevance to specimen under tension load (Fig. 13).

Main reason for this phenomenon is stress distribution in specimen cross-section, Fig. 14. In the case of tension load stress distribution is uniform (Fig. 14a), in contrast to bending load, where linear stress distribution occurs over cross-section of specimen (Fig. 14b).

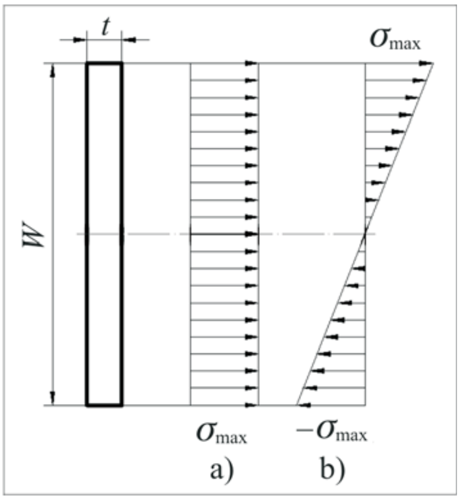

Figure 14 Stress distributions over cross-section: a) tension, b) bending

2.2 Examples of indirect calculations (II type) - through crack – TC01

Following model is chosen as example for indirect calculation (II type):

– specimen type - TC01 (sl.5.5): infinity long plate with width W = 11 in = 279,4 mm and thickness t = 0,1 in = 2,54 mm, with through crack;
– preliminary defined half-crack initial length: c_0 = 0,1 in = 2,54 mm
– specimen is loaded in tension, with remote stress: σ_{max} = S_0 = 10 ksi = 68,95 MPa and stress ratio R = 0.
– material: aluminium alloy 7075-T6 Al;
– given life by number of applied fatigue cycle: N = 100×1000 cycles = 10^5.

In the case of indirect calculation (**III type**), the model identical with the model tested in the section 2.1.1 is selected.

Solution for this type of calculation (**III type**) is scale factor multiplier: j = 1,1136, that represents the intensity of maximum applied load that specimen withstands for preliminary defined working life and under preliminary defined load spectrum. The real maximum load value represents scaled value of load used in calculation: $\sigma_{max} = S_0$ = 10 ksi = 68,95 MPa with scale factor multiplier j = 1,1136 to obtain:

$$\sigma^{\mathrm{REAL}}_{\mathrm{MAX}\ \max} = j \cdot \sigma_{\max} = 11{,}136 \text{ ksi} = 76{,}78 \text{ MPa}.$$

3 Software FRANC 3D

Software FRANC 3D is based on fracture mechanics principles and is used for:

- stress-displacement calculation of structure under static load;
- life prediction (calculation) of structure under dynamically unsteady load (fatigue).

Input parameters are:

- geometry of structure - modeled in appropriate software that is designed for modeling: OSM or others (IDEAS, ANSYS, NASTRAN and PATRAN).
- material properties:

a) for static analysis: E – modulus of elasticity, ν – Poisson ratio, K_C – fracture toughness, ρ – mass density, α – coefficient of thermal expansion;
b) for dynamic analysis the available library NASMAT is used with all necessary parameters for crack growth calculation.

- type and dimensions of initial crack – crack types are given in program.
- boundary conditions: constrains and loads (spectrum).

Based on defined geometry for construction element and crack, there is generated mesh of finite elements (automatically or manually). The user selects the finite element type: triangular or quadrilateral and element size.

Advantage of FRANC 3D software in relevance to NASGRO software is the possibility to modeling entirely new geometries. NASGRO computations are limited only for known specimen types (from offered library). FRANC 3D is able to display simulation of crack propagation (fronts of crack) in the model.

Disadvantage of this software is modeling in OSM modulus, what is not user friendly. However, one can use other programs for this purpose. Results significantly depend on element type of generated mesh and mesh density, because the program is based on FEM. Nevertheless, experience in modeling and manual mesh designing, especially near the crack tip and in the area where geometry changes, leads to convergent solution with satisfactory accuracy. The most frequently used types of thin-walled structure elements are:

- plate or shell element (wing and fuselage skin of airplane);
- hollow cylinder (airplane fuselage, tank).

3.1 Example of thin-walled plate

As an example of the calculation of thin-walled structures, the adopted plate model from the section 2.1.1. (Fig. 7) has been used. Plate and crack dimensions, material and load are identical with the aforementioned example.

Plate modeling is done in OSM software.

Following parameters are defined in software FRANC 3D:

- material: aluminium alloy 7075-T6 Al;
- boundary conditions: plate is fixed on the one side and tension load acts on the other side.

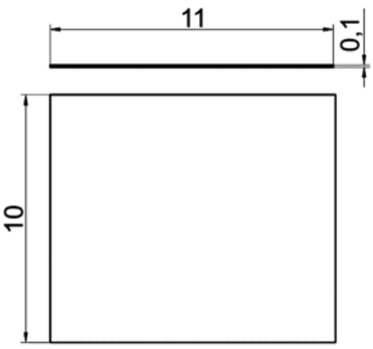

Figure 15 Thin-walled plate

Automatic mesh generation is done just before definition of initial crack in plate model (Fig. 16). Quadrilateral elements are used. Stress-displacement analysis in plate model (Fig. 17) under static load is performed.

Previously displayed analysis shows that stress distribution over the plate model is not uniform due to stress redistribution. Maximum stress value in structure is: σ_{max} = 10 ksi = 68,95 MPa. These values are changed in limits of $\sigma_{max} \in [9, 11]$ ksi ($\sigma_{max} \in [62{,}08, 75{,}84]$ MPa). NASGRO software assumes that stress is uniform across entire plate and that is equal to the stress in infinity. However, in real structural element, all geometry measures are finite and that is the reason for stress distribution (Fig. 17).

Next step is the determination of type and dimension of initial crack. From given library, crack type-through crack is chosen and for half-crack initial length value the following values are taken: c_0 = 0,1 in = 2,54 mm. Then, new finite-element mesh is generated. Determination and generation of new crack fronts are done for defined crack growth step and final number of steps (Fig. 18). Crack propagation occurs under dynamic load in structure. Minimum stress value is obtained by stress ratio R and value of maximum applied stress σ_{max} : $\sigma_{min} = R \cdot \sigma_{max}$.

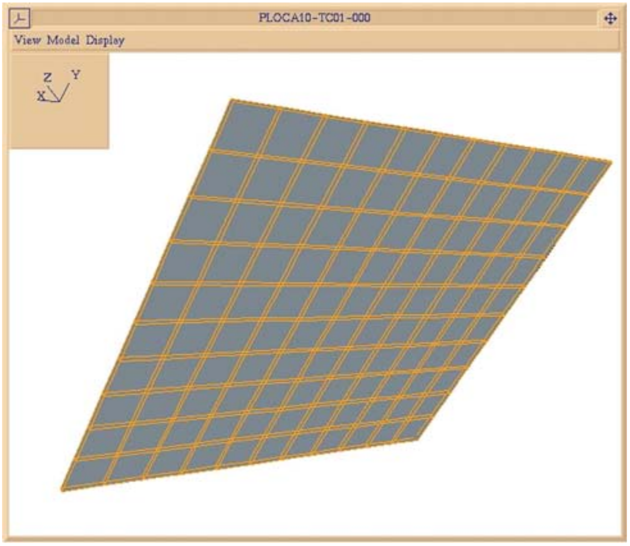

Figure 16 Plate model in FRANC 3D software (Finite Element Mesh)

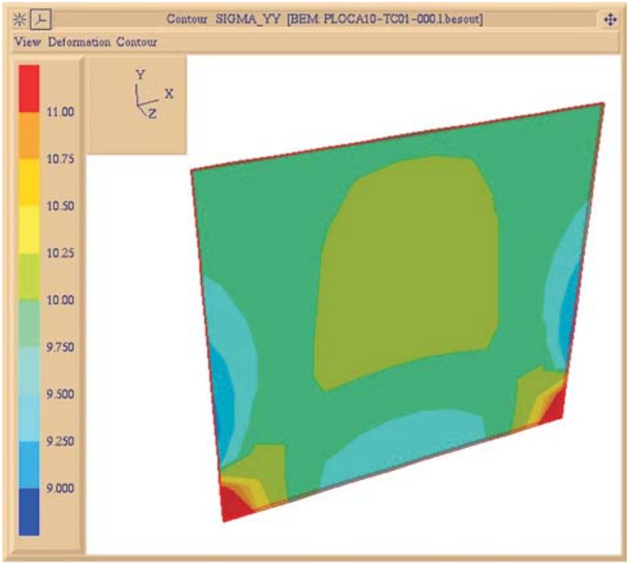

Figure 17 Stress-displacement analysis in plate model

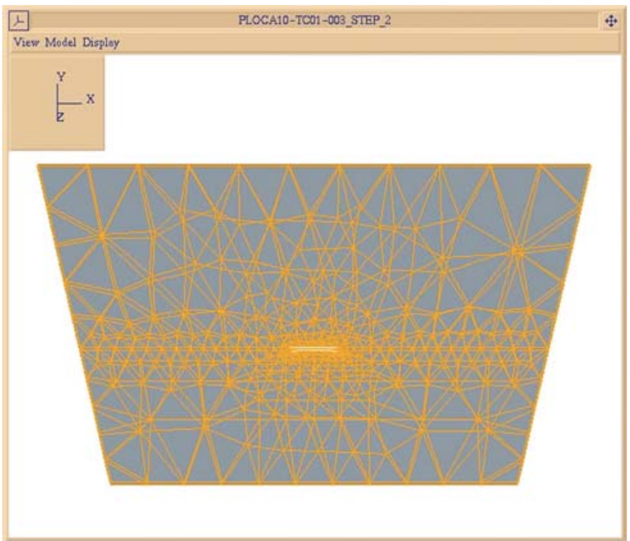

Figure 18 Plate model in FRANC 3D with initial crack and generated cracks fronts (Finite Element Mesh)

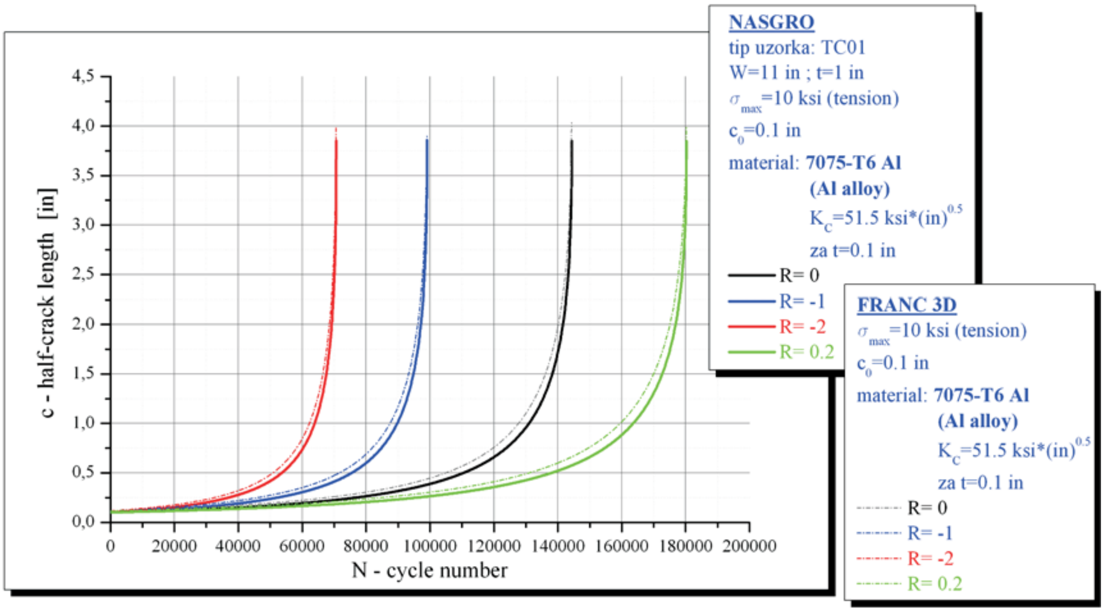

Figure 19 Comparison of dependences on half-crack length and cycles numbers obtained by NASGRO and FRANC 3D

Comparison of results from two different software packages, NASGRO and FRANC 3D, is illustrated in Fig. 19, which shows the dependency of half-crack length, *c* on the number of load cycles, *N*.

4 Conclusions

Comparison of results from two different software packages NASGRO and FRANC 3D gave satisfactory accuracy by achieving matching of two different computational results (construction life represented in the form of the number of applied fatigue cycles, *N*).

Disadvantage of software NASGRO is its inability of complex geometry modeling, in contrast to FRANC 3D software.

Advantages of software usage for structural integrity assessment are:

- saves time
- economic aspect – expensive laboratory investigation is replaced by calculation and simulation
- satisfactory modeling of real constructions and cracks in structures and satisfactory accuracy of derived data that can be applicable in practice.

5 References

[1] Đorđević, P.; Kirin, S.; Sedmak, A.; Džindo, E. Risk analysis in Structural Integrity. // Structural Integrity and Life. 11, 2(2011), pp. 135-138.
[2] Manjgo, M.; Sedmak, A.; Grujić, B. Fracture and fatigue behaviour of NIOMOL 490K welded joint. // Structural Integrity and Life. 8, 3(2008), pp. 149-158.
[3] Burzić, M. Analysis of crack parameters of welded joint of heat resistant steel. // Structural Integrity and Life, 8, 1(2008), pp. 41-54.
[4] Gliha, V.; Burzić, Z.; Vuherer, T. Some Factors Affecting Fatigue Resistance of Welds. // Structural Integrity and Life, 10, 3(2010), pp. 239-244.
[5] Kozak, D.; Gubeljak, N.; Konjatić, P.; Sertić, J. Yield load solutions of heterogeneous welded joints. // International journal of pressure vessels and piping, 86 (2009), pp. 807-812.
[6] Harris Jr, J. A. Engine component retirement for cause, Vol. 1, Executive Summary. AFWAL-TR-87-4609, Wright-Patterson Air Force Base, Ohio, 1987.
[7] Fatigue Crack Growth Computer program "NASGRO", Reference Manual, National Aeronautics and Space Administration, London B. Johnson Space Center, Houston, Texas 77058-3696, August 2002.
[8] FRANC 3D, Menu & Dialog Manual, July 1998.
[9] FRANC 3D, Tutorial, July 1998.

Authors' addresses:

MSc Danijela Živojinović, PhD student
Technical College
Bulevar Zorana Đinđića 152-a
Belgrade, Serbia

Dr Miodrag Arsić
IMS
Bulevar Vojvode Mišića 43
Belgrade, Serbia

Professor Aleksandar Sedmak
University of Belgrade
Faculty of Mechanical Engineering
Kraljice Marije 16
Belgrade, Serbia
e-mail: asedmak@mas.bg.ac.rs

Dr Snežana Kirin
Innovation Center of Mechanical Engineering Faculty
Kraljice Marije 16
Belgrade, Serbia

Dr Radoljub Tomić
RPC
Prva Petoletka
Trstenik, Serbia