7FP ***AIRCRAFT INTEGRATED STRUCTURAL HEALTH ASSESSMENT II***

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Remaining strength and lifetime of the Al alloy aircraft components

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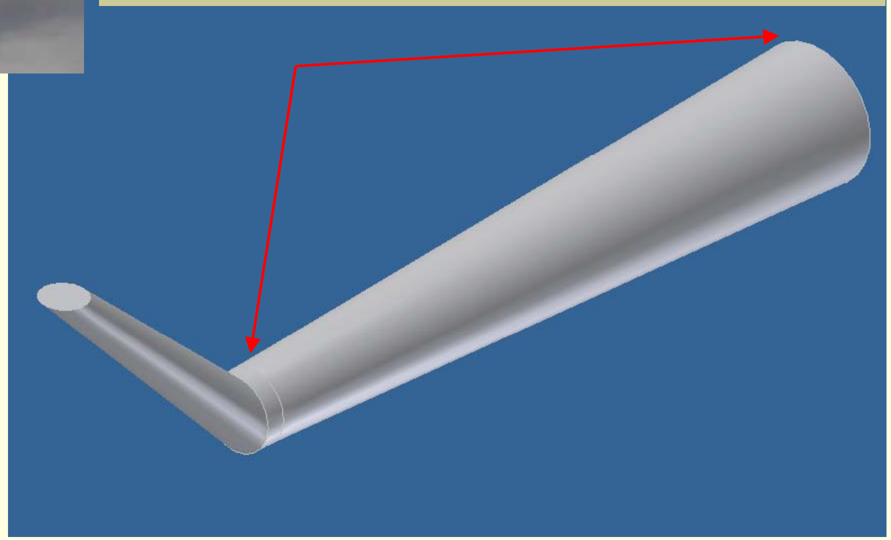
Contents

Introduction: The function of tail beam, and its location in structure of helicopter

Intention: To create experimental SHM system (ESHM) for the tail beam and estimation of its reliability and technical and economical efficiency.

- The beam has the form of the truncated cone with a length of 5485 mm, i.e. the length of the beam. The base diameters are 1000 and 550 mm respectively.



Introduction

Figure 1. Common view of the MI8 helicopter tail beam before mounting for full-scale fatigue testing

Basic regularities of the fatigue failure of thin-walled structure

1) Points of stress concentration: the free curvilinear surface of a structural element

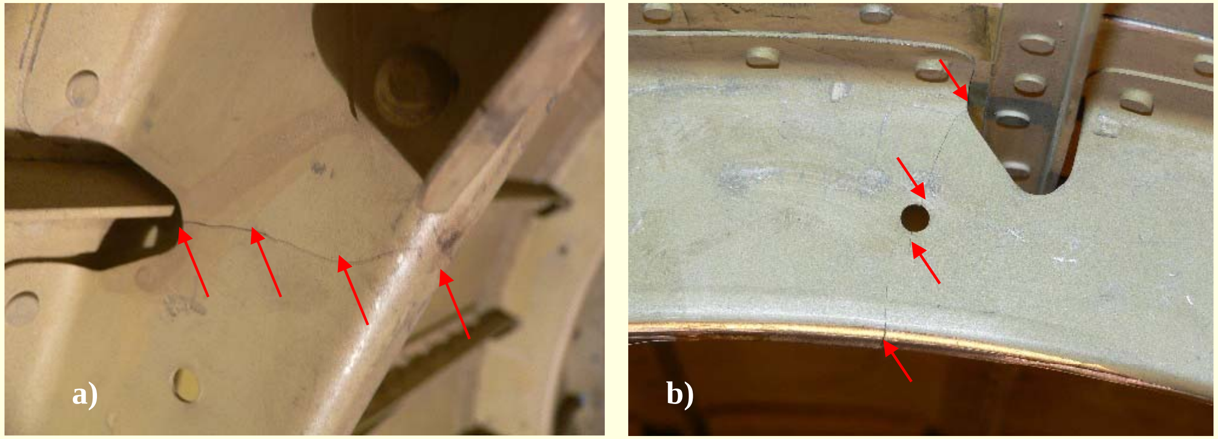


Figure 2. First kind of the fatigue crack: a) on the free curvilinear surface of a frame, b) the free hole in a thin wall of a frame

Basic regularities of the fatigue failure of thin-walled structure

2) Points of stress concentration: the free curvilinear surface of a structural element

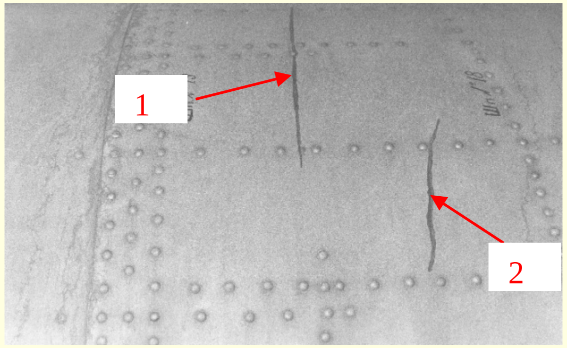


Figure 3. The fatigue cracks in a skin are initialized by the stress concentration 1) near the most loaded fastening point in rivet-joint 2) on small hole in skin

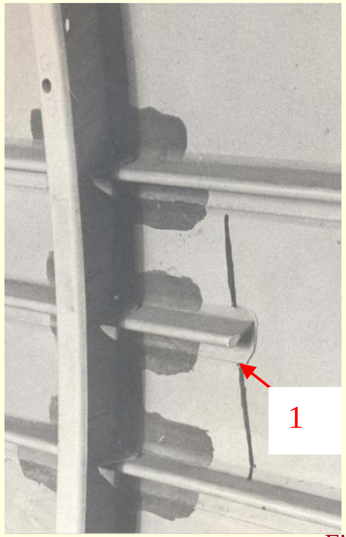


Figure 4. The fatigue crack in a skin is initialized by stress concentration near last fastening point 1 in point-welded connection with tip of a stringer

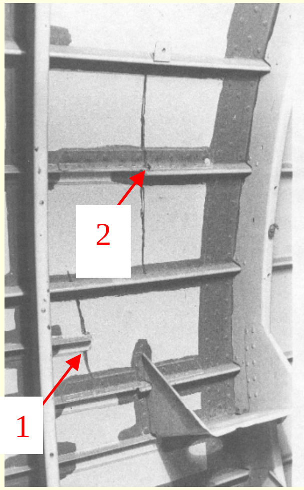
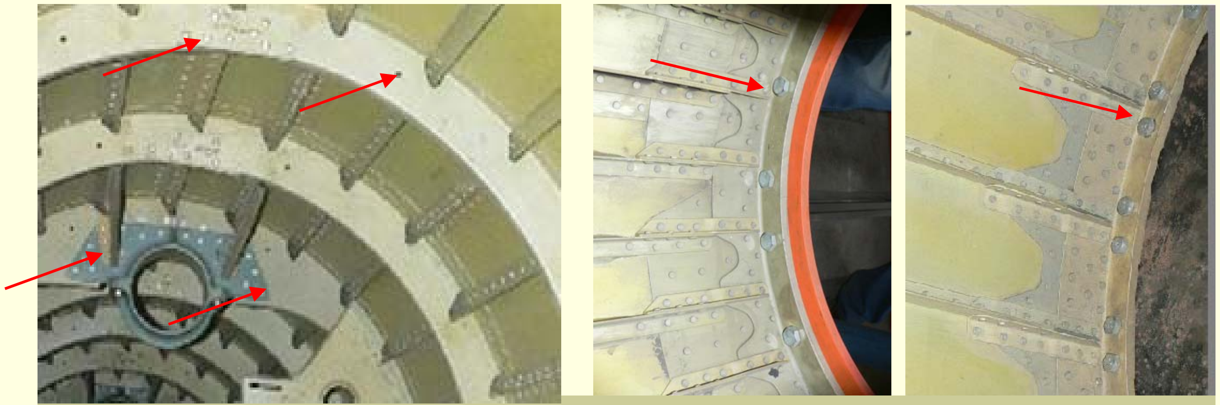


Figure 5. The fatigue cracks in a skin are initialized by the stress concentration 1) near last fastening point 1 in point-welded connection with tip of a stringer 2) near the most loaded fastening point in rivet-joint of two parts of a stringer

Basic regularities of the fatigue failure of thin-walled structure

Typical elements of a skeleton of a design (frames and stringers). The damages must be detected near each of large multiplicity of stress concentrators (Figure 2a). This part also includes the bolt-joints with others components of aircraft (Figure 2b).



a) b)

Figure 2. Typical points of the stress concentration in structural elements of the MI8 helicopter tail beam skeleton (a) and the bolt-joints with others components of aircraft (b).

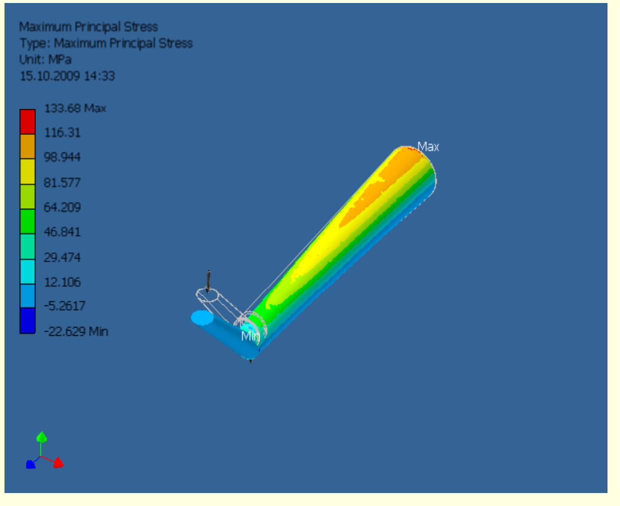
Fatigue damage and remaining lifetime of Al part simulation

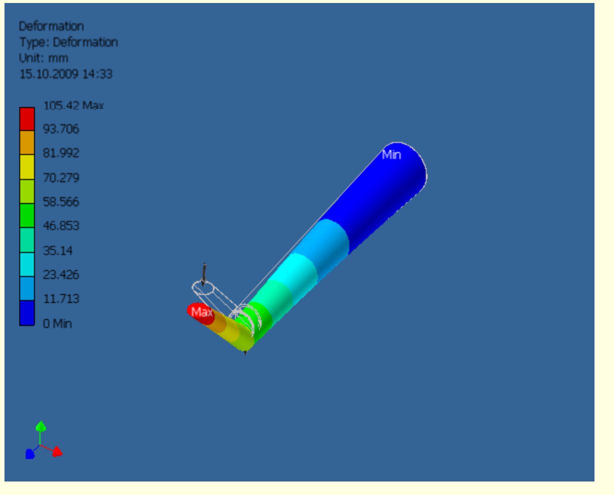
- Geometry and structural modeling
- Materials
- Loading
- Stress analysis and Stress intensity factor
- Fatigue crack growth modeling
- Remaining lifetime prediction

Stress analysis

Multilevel the procedure of FEA

1) Full scale component of aircraft must define the averaged values of internal forces acting on the basic units of aircraft component



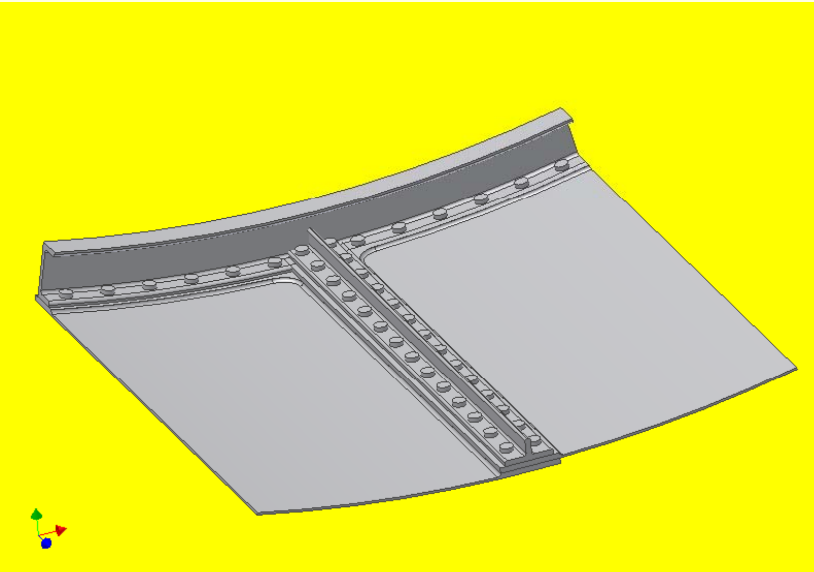


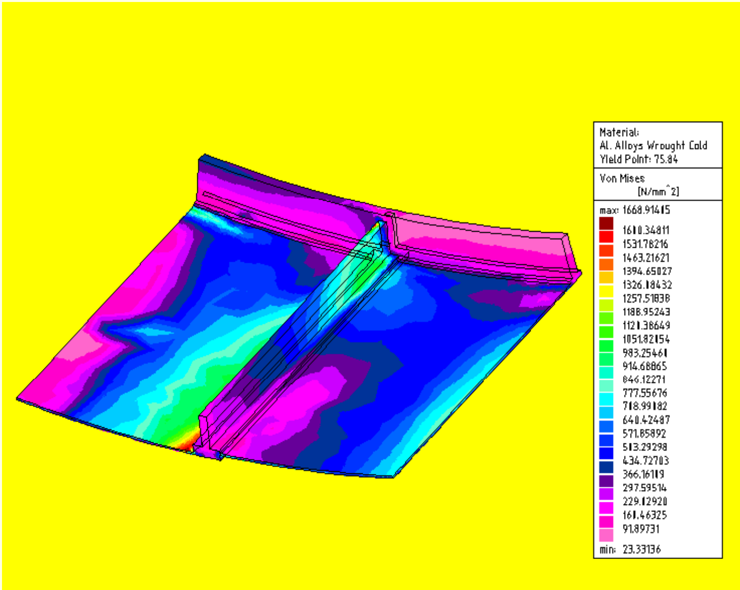
a) b)

Figure 6. Landing position: Maximum Principal Stress (a) and beam deformation (b)

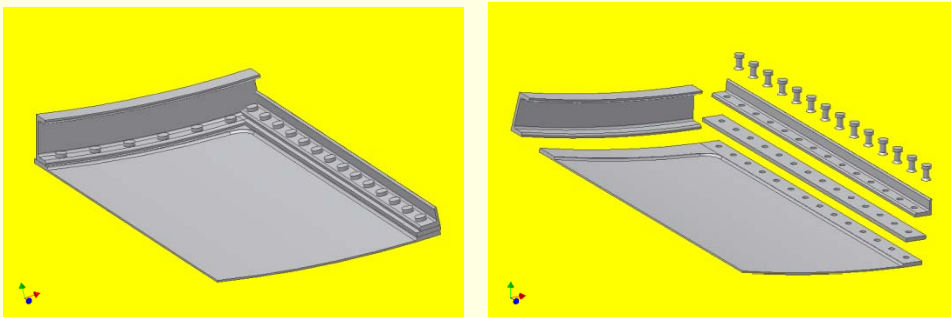
Stress analysis

2) The stresses and contact forces of interaction between the elements of a unit





Stress analysis



a) b)

Figure 7. The CAD-model of a structural unit in a zone of longitudinal rivet-joint of sheets: common view (a) and the structural parts of an unit (b)

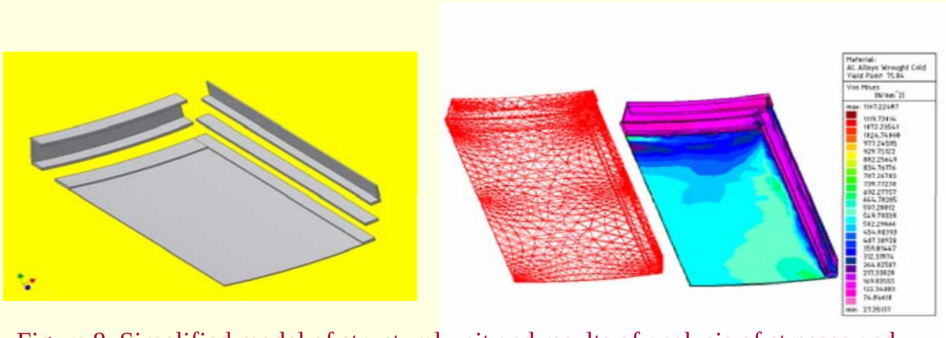


Figure 8. Simplified model of structural unit and results of analysis of stresses and contact forces of interaction between the elements

Stress analysis and Stress intensity factor

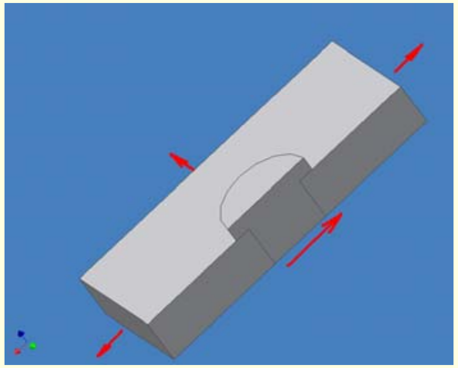


Figure 9. The model of a fastening point prepared for FEA

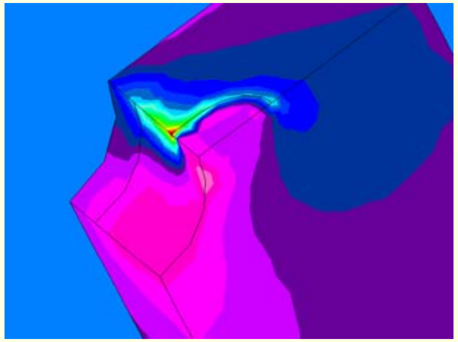
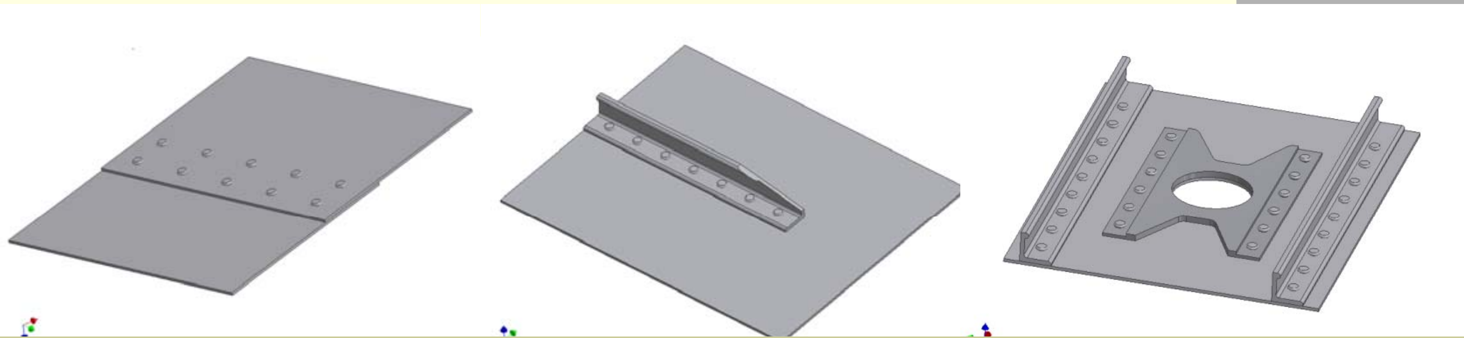


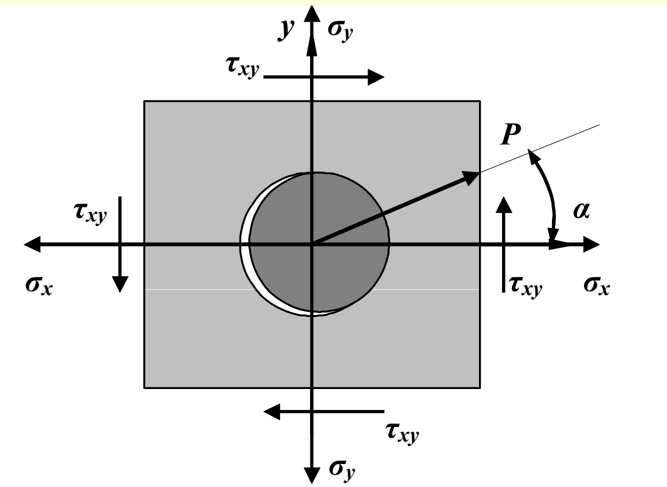
Figure 10. Stress analysis of structural element with a crack from a hole of fastening point

$$\overline{K}(\theta)=\frac{K(\theta)}{\sigma\sqrt{\pi a}}=f\left(\theta,\frac{a}{d},\frac{a}{b},\frac{\sigma_2}{\sigma},\ldots\right)$$

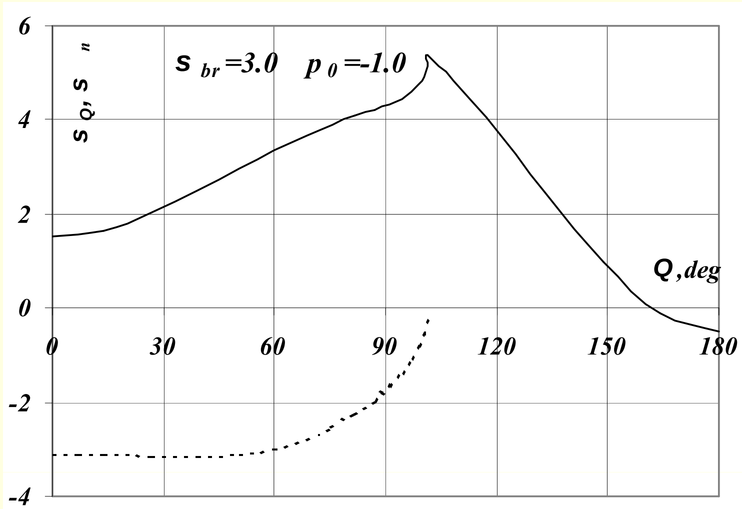
Stress analysis and fatigue crack initiation



The examples of the rivet joints application in the aircraft structures.

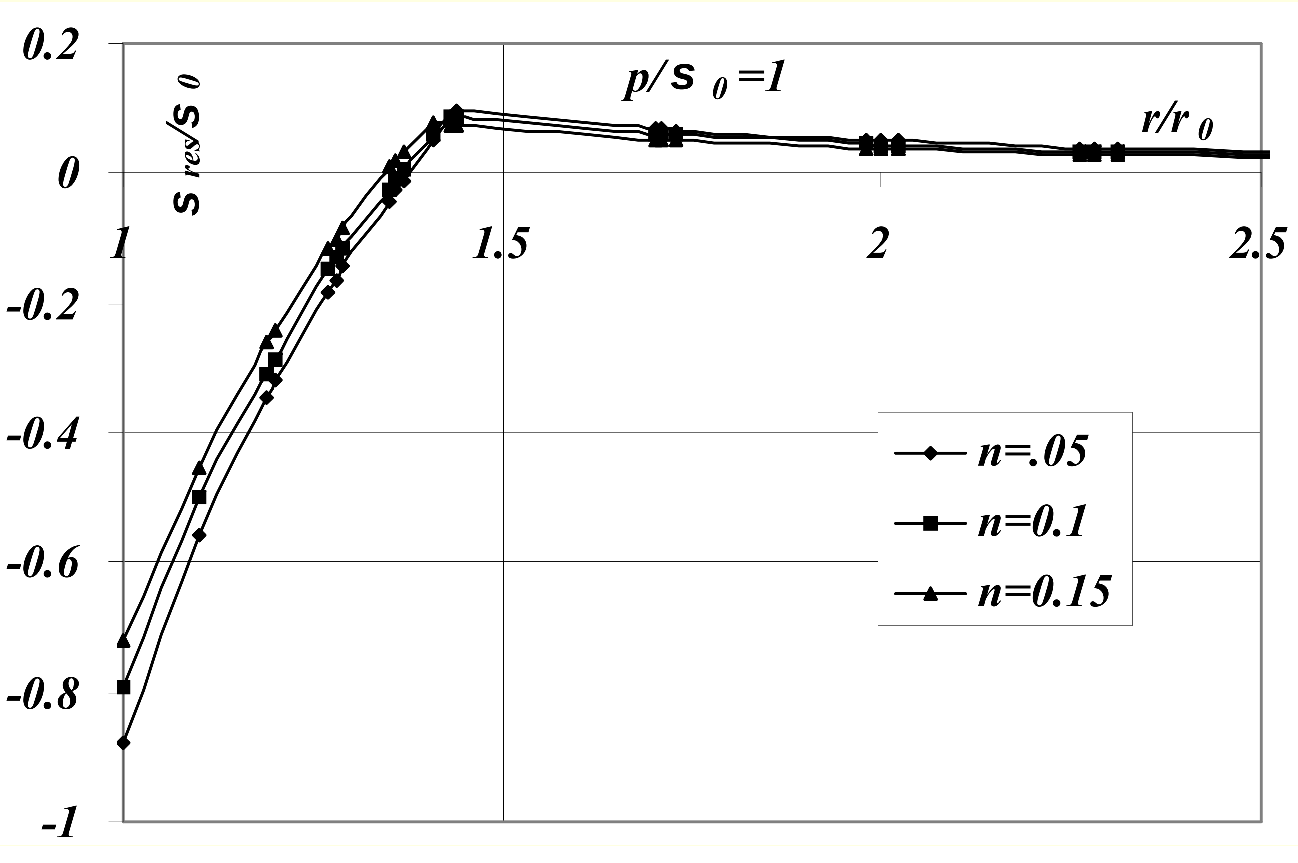


Scheme of an isolated fastening

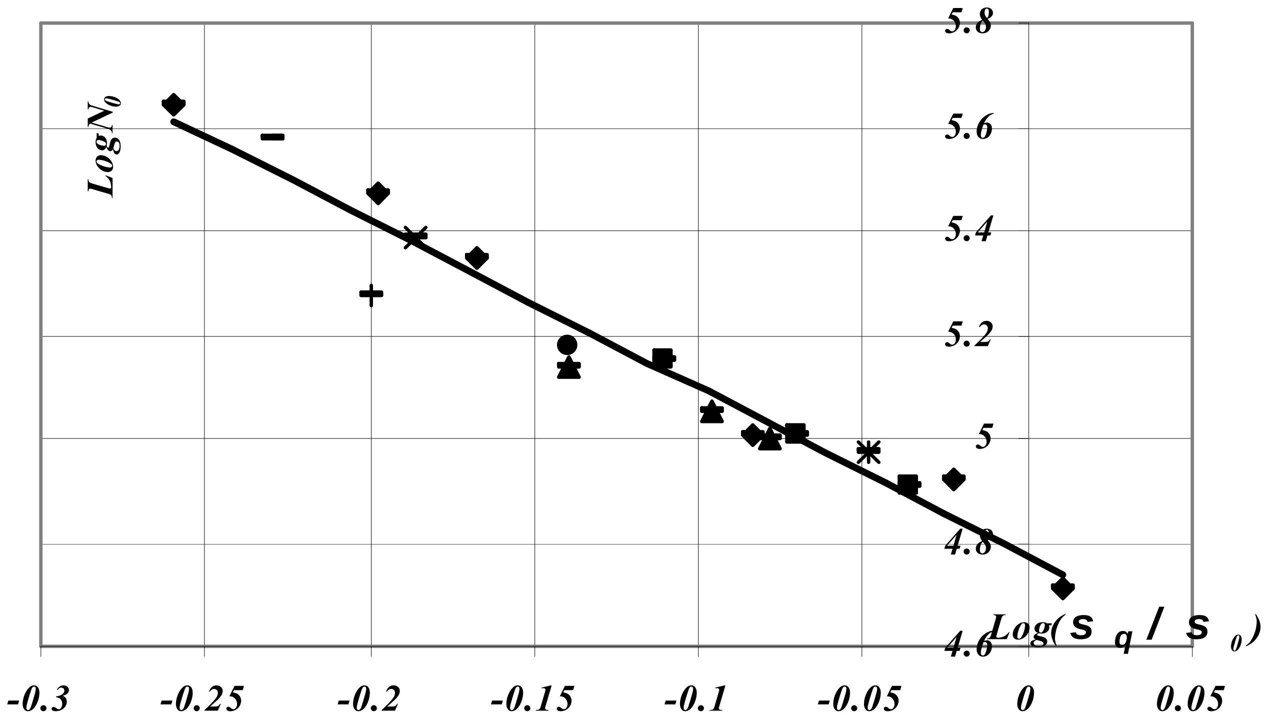


The distributions of circumferential and contact stresses on a surface of a hole at ***p0*** = -1.0

Stress analysis and fatigue crack initiation



Stress analysis and fatigue crack initiation



Local curve of fatigue

Remaining strength estimation

1) Model of the small scale plasticity

$$K_I = \sigma\sqrt{\pi a}\, f(\lambda) \qquad \sigma\sqrt{\pi a_{eff}}\, f(\lambda) = K_{Ic} \qquad K_I = K_{Ic}$$

2) Model of invariant ***J***-integral.

$$J_I = J_{Ic}$$

3) Experimental data

Fatigue crack growth

$$\frac{dl}{dN} = C(\Delta K)^m$$

Possible solutions

Theoretical modeling:
- Physical models of residual and active stresses interaction
- Models of crack open/closure
- Continuum mechanics models

Using the data of crack propagation at operation loading:
- Aircraft C-130
- Crack growth indication by the special device

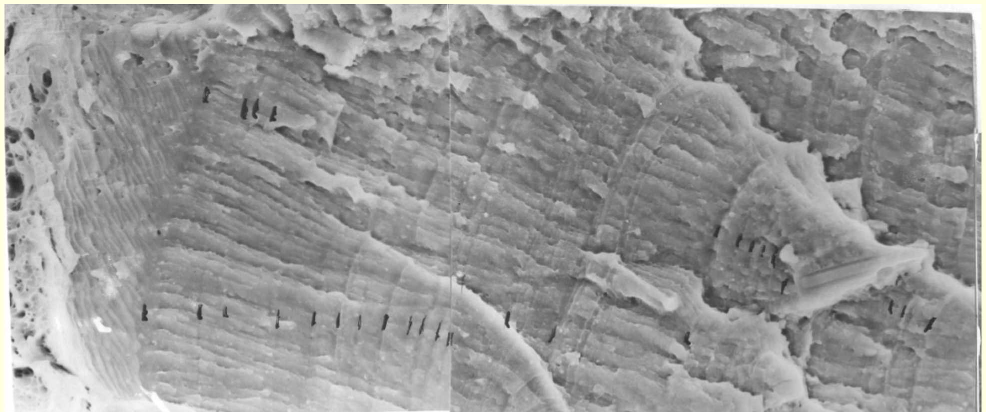


Figure 11. View of a crack surface of CGI after 26 flights (x2000). The crack increments in separate flights are noted by the markers

Fatigue crack growth

Investigation of the fatigue crack growth in a skin of the MI8 helicopter tail beam at full scale test

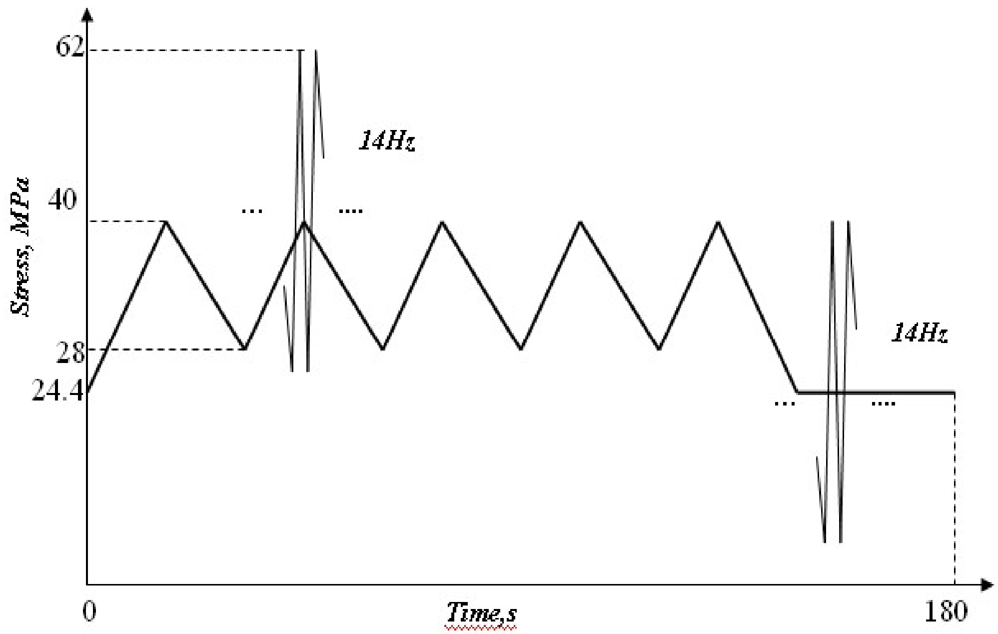


Figure 7. Loading spectrum

Fatigue crack growth

Investigation of the fatigue crack growth in a skin of the MI8 helicopter tail beam at full scale test using the crack growth indicator (CGI)

Table 1. Paris law parameters comparison

Nr	Specimen	Mean of constant ***C******	Standard deviation	95% confidence intervals of constant ***C******	
				low	upper
1.	Flat specimen	$2.55 \cdot 10^{-9}$	$1.71 \cdot 10^{-10}$	$2.45 \cdot 10^{-9}$	$2.64 \cdot 10^{-9}$
2.	CGI	$2.51 \cdot 10^{-9}$	$3.48 \cdot 10^{-10}$	$2.39 \cdot 10^{-9}$	$2.63 \cdot 10^{-9}$

Engineering model of prediction of fatigue crack propagation

- It is postulated a crack reaches at some point, if the condition of low-cycle fatigue destruction of Manson-Coffin is performed
- The Miner's rule of fatigue damage accumulation
- Periodic flight-by-flight loading
- The material has power tensile diagram
- Special strain distribution in plastic zone

Engineering model of prediction of fatigue crack propagation: Flight-by-flight loading

Simplified load of typical flight

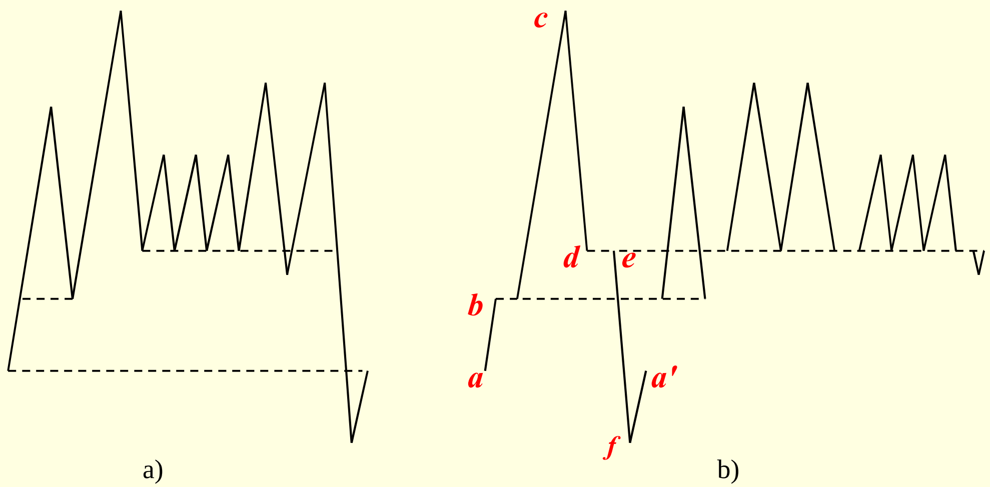


Figure 12. One typical flight load (a) and its transformation (b): ***a-b-c-d-e-f-a'*** is basic cycle

Engineering model of prediction of fatigue crack propagation: basic equation

The basic equation of fatigue crack growth

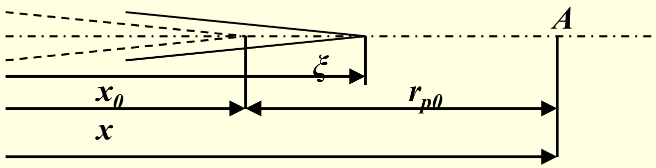


Figure 13. The scheme of fatigue damage accumulation is the size of reverse plastic zone from basic cycle of load

$$\sum_{i=0}^{q}\int_{0}^{N_f}\frac{\overline{N}_i dN}{N_{fi}}=1$$

$$N_{fi}(x,\xi)=\frac{C}{\left(\Delta e_{pi}\right)^k}$$

$$\sum_{i=0}^{q}\int_{0}^{N_f}\left[\left(\Delta\varepsilon(x,\xi)_{pij}\right)^k\overline{N}_i\right]dN=C$$

$$dN=\frac{d\xi}{v(\xi)}$$

$$\sum_{i=0}^{q}\int_{x_0}^{x}\left[\left(\Delta\varepsilon(x,\xi)_{pij}\right)^k\overline{N}_i\right]\frac{d\xi}{v(\xi)}=C$$

Engineering model of prediction of fatigue crack propagation: Strain distribution

1)The material has power tensile diagram

$$\frac{\sigma}{\sigma_0} = \begin{cases} \dfrac{\varepsilon}{\varepsilon_0}, & if\ |\varepsilon| \le \varepsilon_0 \\ sign(\varepsilon)\left(\dfrac{|\varepsilon|}{\varepsilon_0}\right)^n, & if\ |\varepsilon| \ge \varepsilon_0 \end{cases}$$

where σ_0 is yield stress, $\varepsilon_0 = \dfrac{\sigma_0}{E}$, and n *is degree of hardening.*

2) The strain distribution in plastic zone

$$\varepsilon(r) = \varepsilon_0\left(\frac{r_p}{r}\right)^{\frac{1}{1+n}} \qquad r_p = \frac{1}{\pi(1+n)}\left(\frac{K_I}{\sigma_0}\right)^2 \qquad \varepsilon_p = \varepsilon_0\left[\left(\frac{r_p}{r}\right)^{\frac{1}{1+n}} - \left(\frac{r_p}{r}\right)^{\frac{n}{1+n}}\right]$$

2) The strain distribution in cyclic plastic zone

$$\Delta\varepsilon_{pi} = \bar{\varepsilon}_0\left[\left(\frac{\bar{r}_{pi}}{r}\right)^{\frac{1}{1+n}} - \left(\frac{\bar{r}_{pi}}{r}\right)^{\frac{n}{1+n}}\right] \qquad \bar{\varepsilon}_0 = \frac{2\sigma_0}{E} \qquad \bar{r}_{pi} = \frac{1}{\pi(1+n)}\left(\frac{\Delta K_{Ii}}{2\sigma_0}\right)^2$$

Engineering model of prediction of fatigue crack propagation: Final form the BE

Critical point of destruction

$$r^{*} = r_{pc}\left(\frac{\varepsilon_0}{\varepsilon_f}\right)^{1+n} \qquad r_{pc} = \frac{K_{Ic}^{2}}{\pi(1+n)\sigma_0^{2}}$$

Final form of the basic equation (BE) of fatigue crack growth

$$\sum_{i=0}^{q}\int_{x_i}^{x-r^{*}}\left\{\bar{\varepsilon}_0\left[\left(\frac{\bar{r}_{pi}}{x-\xi}\right)^{\frac{1}{1+n}}-\left(\frac{\bar{r}_{pi}}{x-\xi}\right)^{\frac{n}{1+n}}\right]\right\}^{k}\bar{N}_i\,\frac{d\xi}{v(\xi)}=C$$

A special case of fatigue crack growth

If a fatigue crack rate can be acceptable as constant along a distance equal to size of cyclic plastic zone, then

$$v = \frac{1}{C}\sum_{i=0}^{q}\int_{x_i}^{x-r^*}\left\{\bar{\varepsilon}_0\left[\left(\frac{\bar{r}_{pi}}{x-\xi}\right)^{\frac{1}{1+n}} - \left(\frac{\bar{r}_{pi}}{x-\xi}\right)^{\frac{n}{1+n}}\right]\right\}^k \bar{N}_i d\xi$$

$$v = \frac{\bar{\varepsilon}_0^{\,k}}{C}\sum_{i=0}^{q}\bar{N}_i\left\{\bar{r}_{pi}^{\frac{k}{1+n}}\frac{1+n}{k-1-n}\left[\left(r^*\right)^{\frac{1+n-k}{1+n}} - \left(\bar{r}_{pi}\right)^{\frac{1+n-k}{1+n}}\right] - k\bar{r}_{pi}^{\frac{k+n-1}{1+n}}\frac{1+n}{k-2}\left[\left(r^*\right)^{\frac{2-k}{1+n}} - \left(\bar{r}_{pi}\right)^{\frac{2-k}{1+n}}\right]\right\}$$

If you ignore the small components in a formula

$$v \approx v_0\left[1 + \sum_{i=1}^{q}\frac{\bar{N}_i}{\bar{N}_0}\left(\frac{\Delta K_{Ii}}{\Delta K_{I0}}\right)^{\frac{2k}{1+n}}\right] \qquad v_0 \approx A\left(\Delta K_{I0}\right)^{\frac{2k}{1+n}} \qquad A = \frac{4^{\frac{nk}{1+n}}\bar{N}_0}{\left(E\varepsilon_f'\right)^k \pi(k-1-n)}\frac{\sigma_0^{k(1+n)}}{K_{Ic}^{\frac{2(k-1-n)}{1+n}}}$$

Conclusions

- The establishment numerical model for the linking parameters of damage with remaining lifetime (remaining strength) in the most general case should provide the following: structure, material properties, mechanical loading and environmental effect, possible damage and its parameters and other information
- The multilevel analysis of stresses (finally with the possible damages) must give the data for the analysis of remaining strain and remaining lifetime
- The original model of fatigue crack propagation was developed for crack growth predicting together with the original estimate of variable amplitude effect. Physical base of model is Manson-Coffin's equation.
- Model well correlates with known regularities of the fatigue crack growing and is good for application of remaining lifetime assessment

Thanks you for your attention!

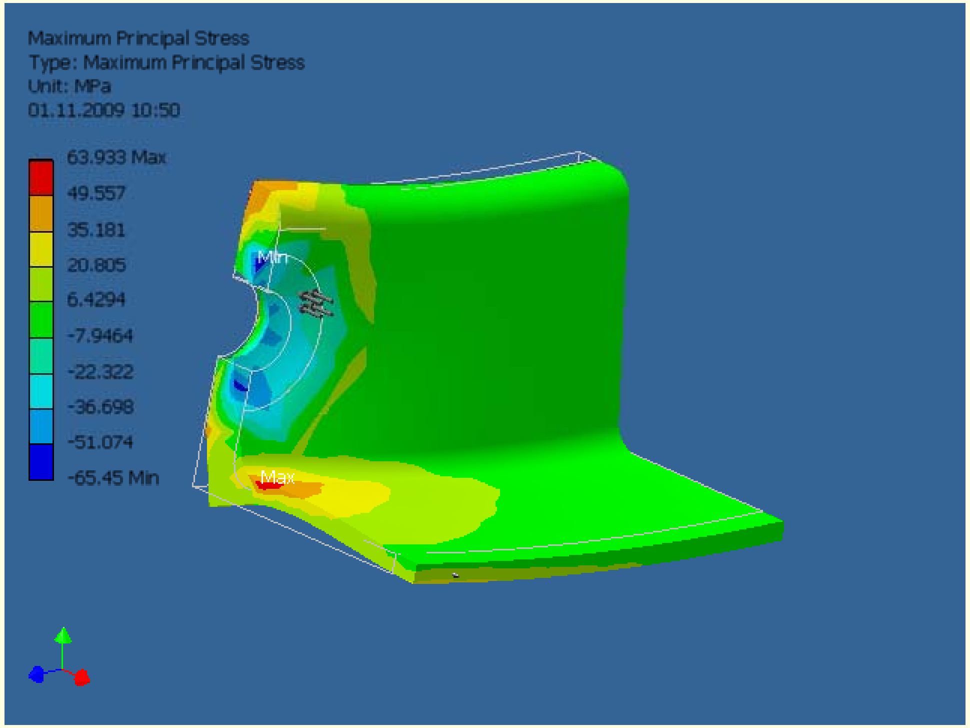
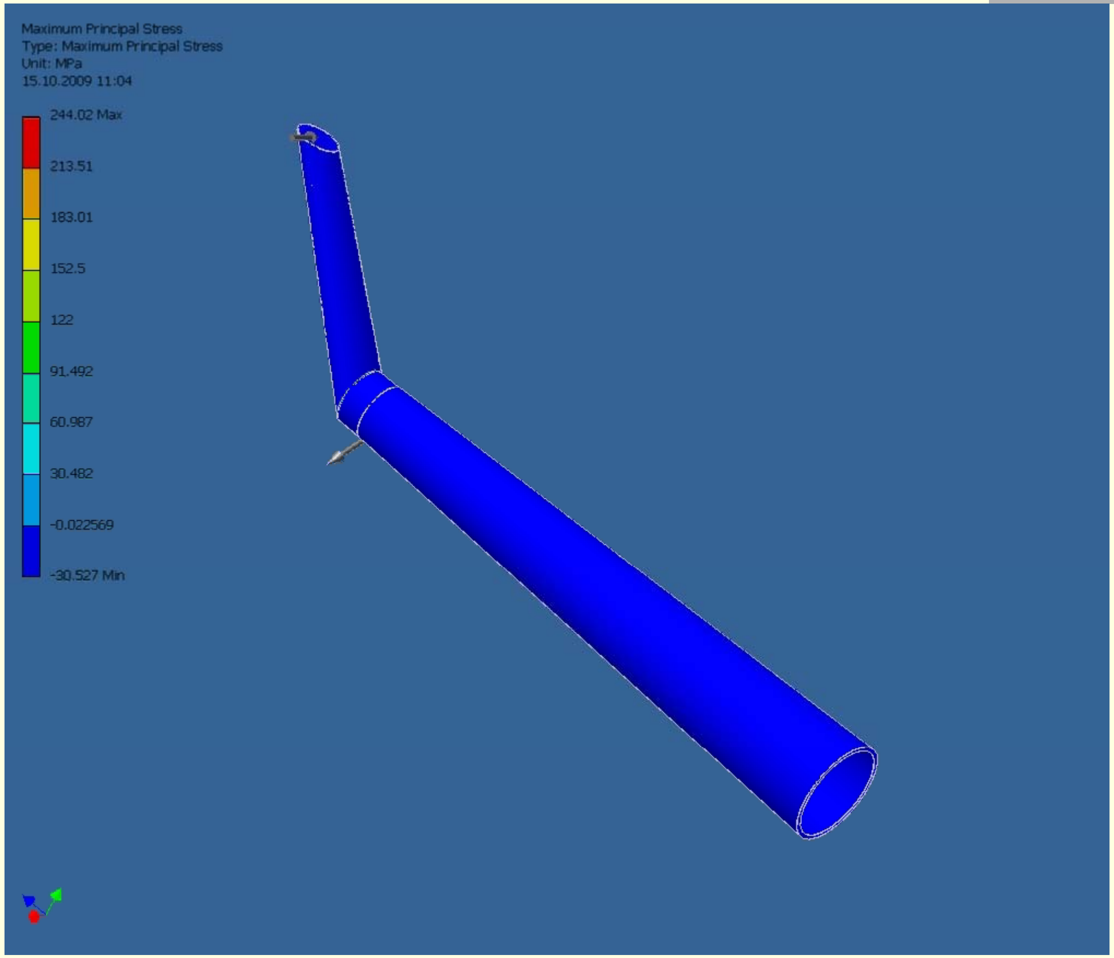


Figure 13. Maximum Principal Stress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Unit: MPa
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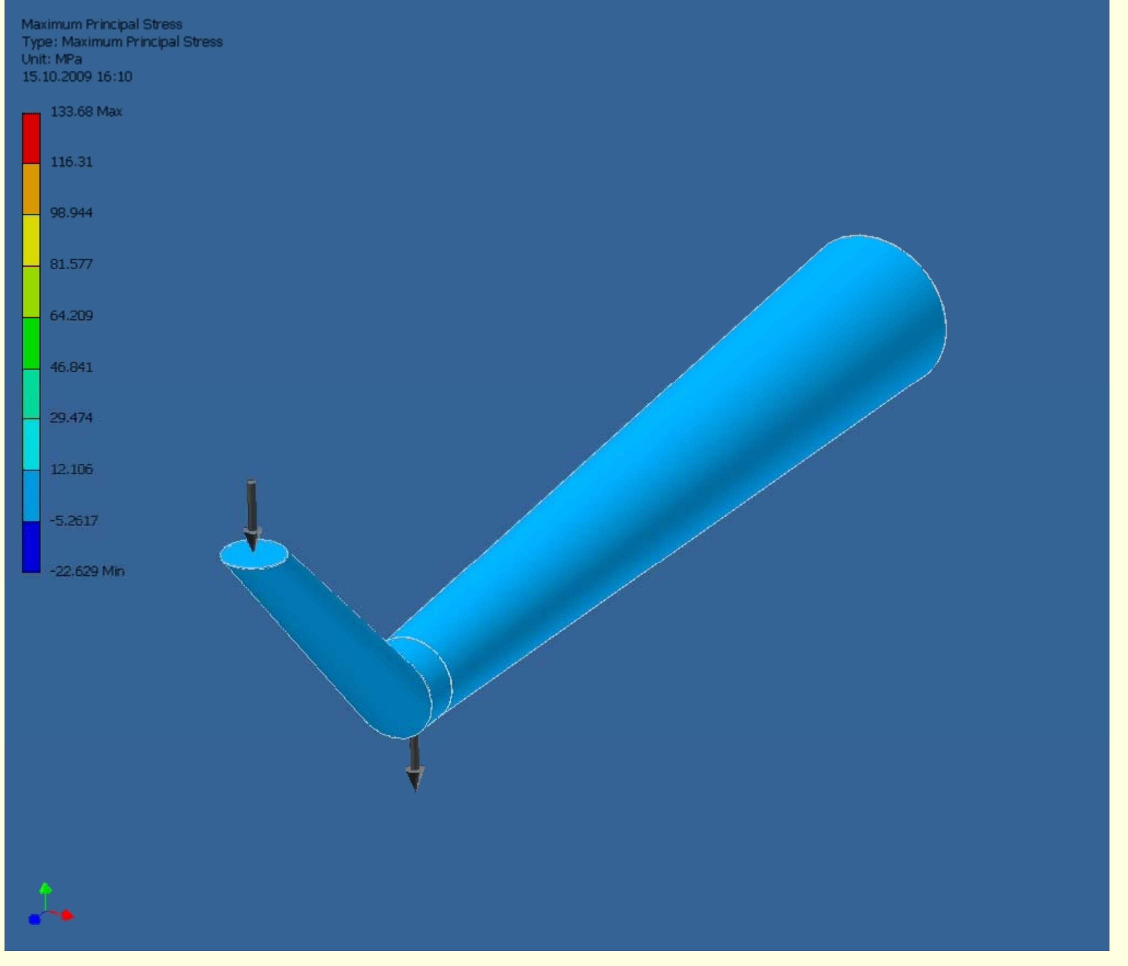
-30.527 Min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Unit: MPa
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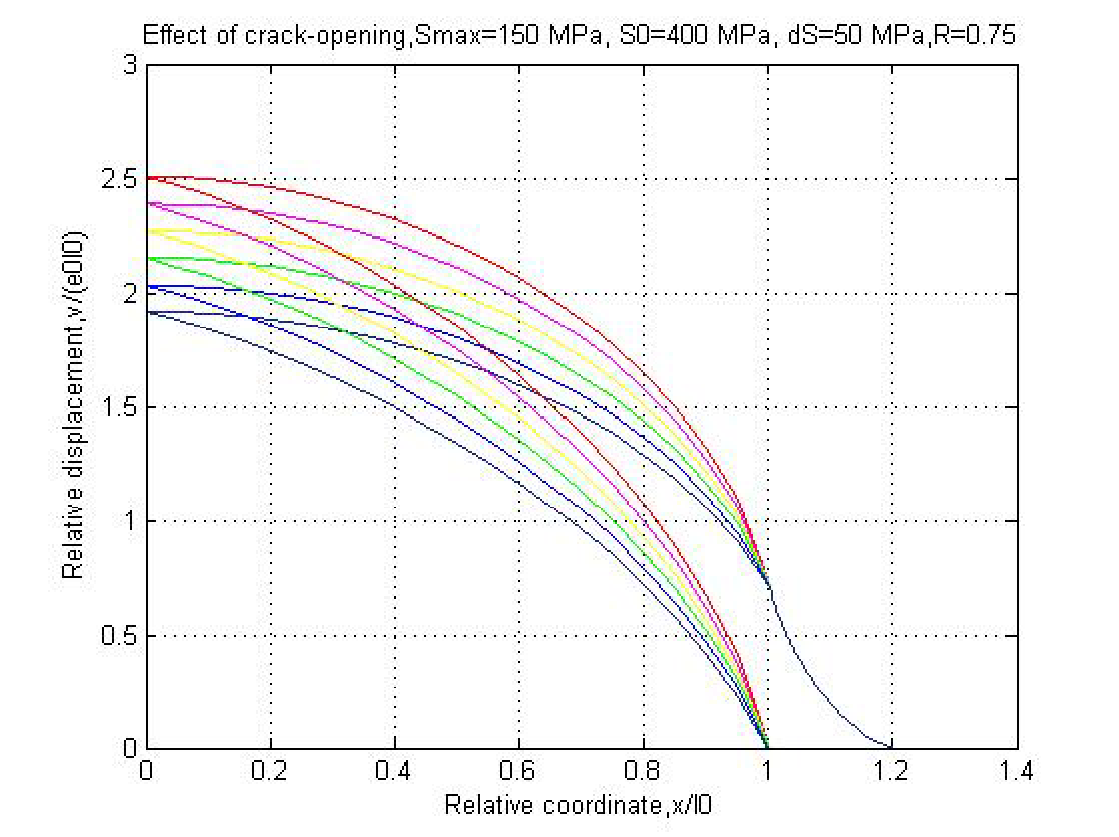
Effect of crack-opening,Smax=150 MPa, S0=400 MPa, dS=50 MPa,R=0.75
Relative displacement,v/(e0l0)
Relative coordinate,x/l0
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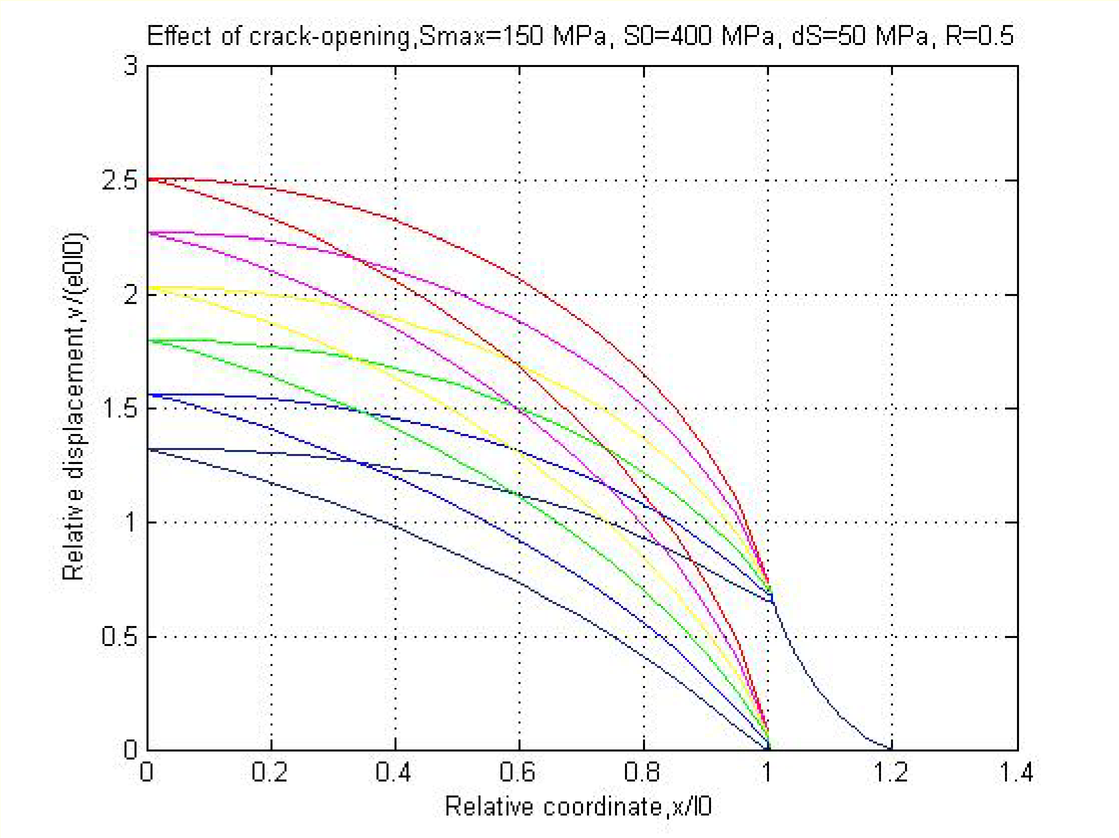
2
1.5
1
0.5
0
0
0.2
0.4
0.6
0.8
1
1.2
1.4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Relative displacement,v/(e0l0)
Relative coordinate,x/l0
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2.5
3
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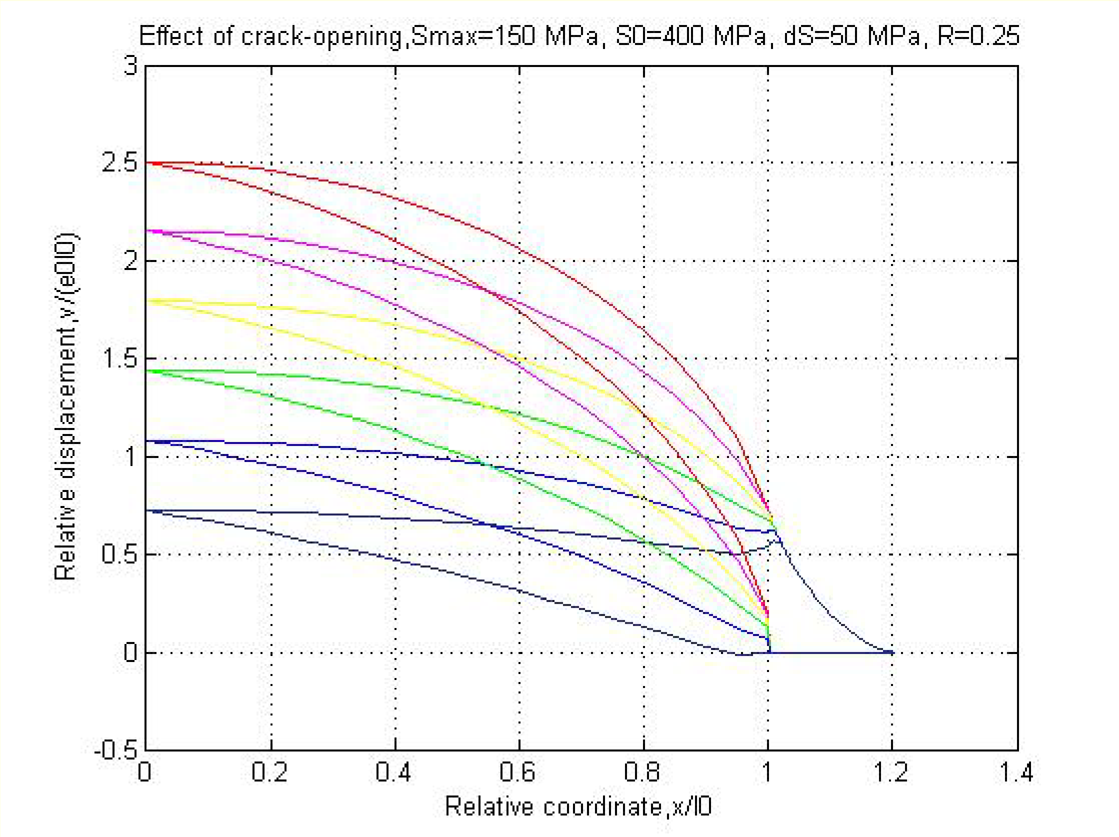
0.4
0.6
0.8
1.2
1.4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Relative displacement,v/(e0l0)
Relative coordinate,x/l0
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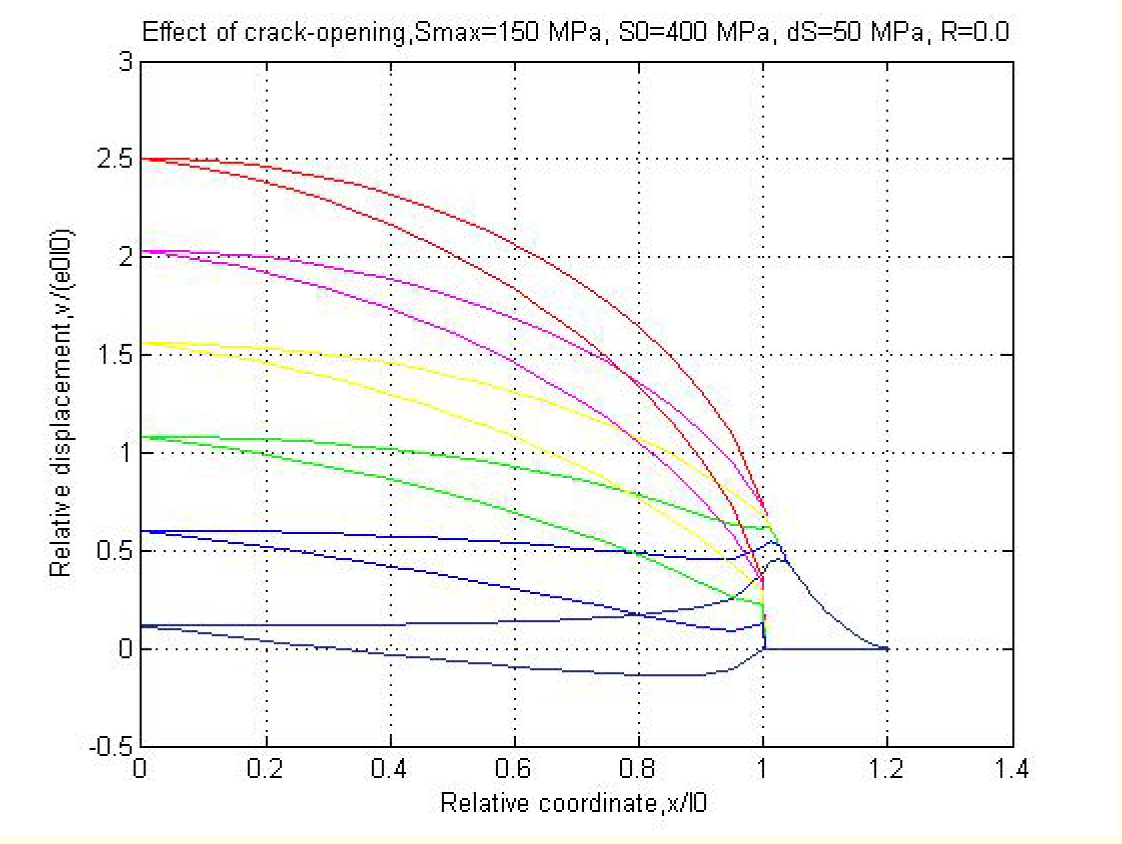
2.5
2
1.5
1
0.5
0
-0.5
0
0.2
0.4
0.6
0.8
1
1.2
1.4



Effect of crack-opening,Smax=150 MPa, S0=400 MPa, dS=50 MPa, R=0.0
Relative displacement,v/(e0l0)
Relative coordinate,x/l0
3
2.5
2
1.5
1
0.5
0
-0.5
0
0.2
0.4
0.6
0.8
1
1.2
1.4