Advanced methods for reliability and fracture risk assessment of structural elements with crack-like defects

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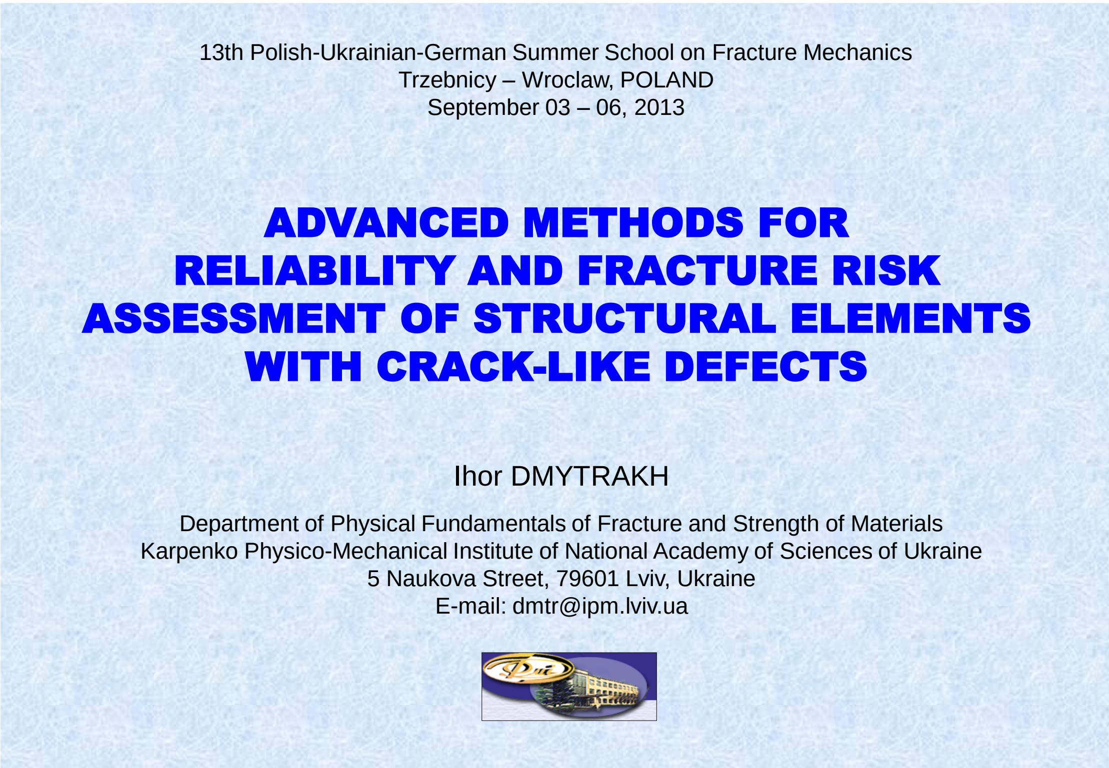
Trzebnica, 3–6 th September 2013



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OUTLINE OF LECTURE

1. Introduction
2. Conception of Index of Structural Element Resistance to Crack Growth
3. Strength and Fracture Risk Assessment of Typical Structural Elements under Static Loading
4. Durability Assessment of Defected Structural Elements under Cyclic Loading in Operating Environments
5. Conclusions

1. INTRODUCTION

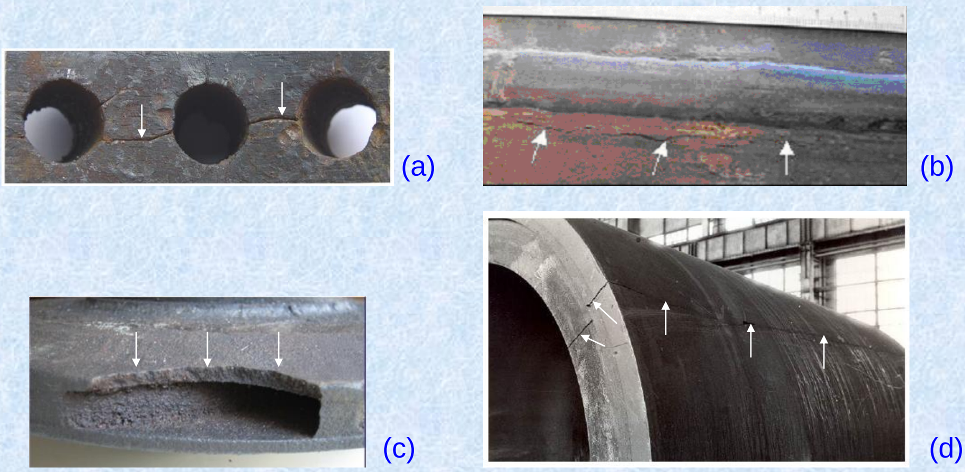


Fig. 1.1. Samples of typical damages and defects in elements of long-term operation structures in different branches of industry:
a – heat-and-power; b – pipeline transport; c – chemical industry; d – mechanical engineering..

2. CONCEPTION OF INDEX OF STRUCTURAL ELEMENT RESISTANCE TO CRACK GROWTH *

Tóth L. Crack propagation sensitivity index as the tool to promote the fracture mechanics concepts // Materials Science. – 2001. – **37, № 2. – С. 63–68.*

$$\boxed{\lambda = \frac{dK_I(a)}{da}} \qquad (2.1)$$

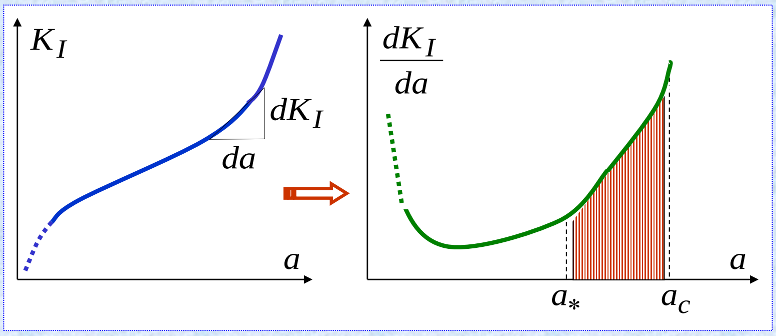


Fig. 2.1. Schematic view of determination of index of structural element resistance to crack growth λ

$$a_* < a_c \qquad a_* < a < a_c \qquad K_I(a_c) = K_{IC} \qquad (2.2)$$

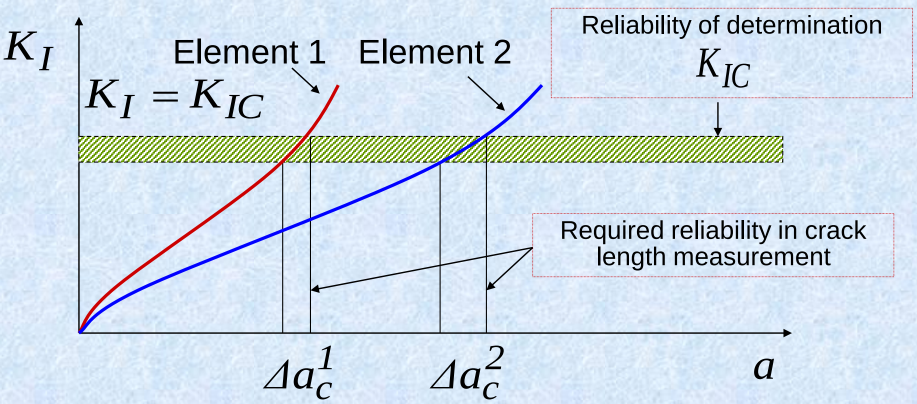


Fig. 2.2. Determining of required reliability of critical crack length a_c measurement for different structural elements

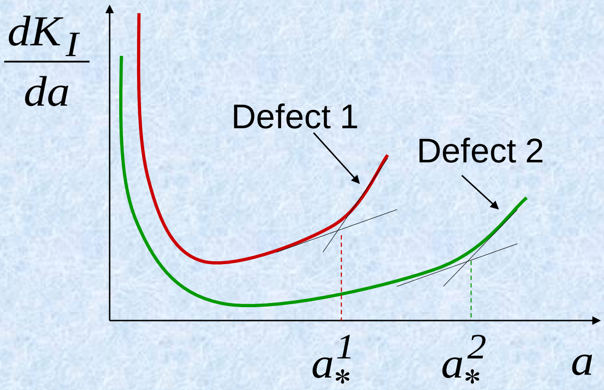


Fig. 2.3. Comparative assessment of danger of different defects in identical structural elements under identical operating conditions

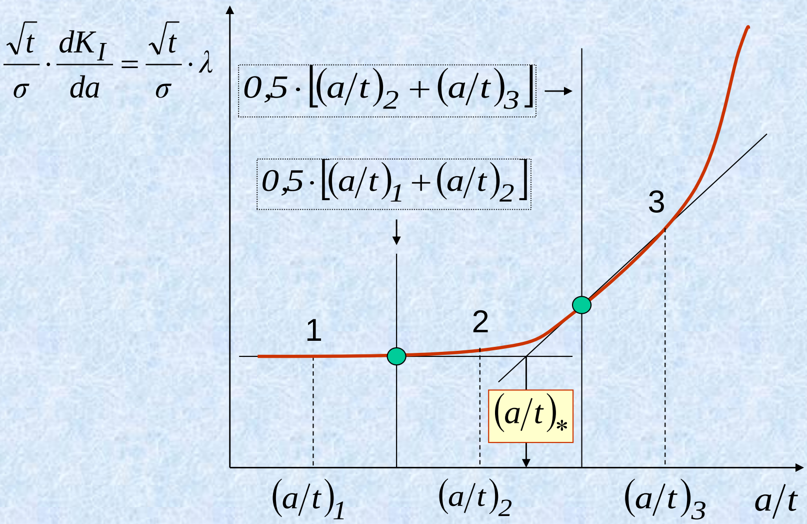
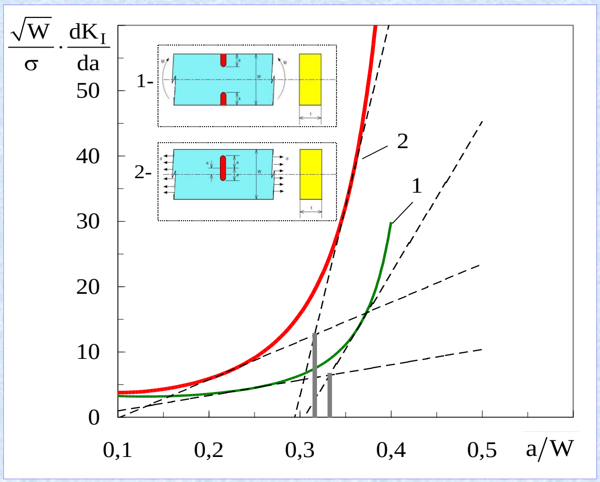


Fig. 2.4. General scheme of determination of characteristic defect size *(a/t)*$_*$

$$\left(\frac{a}{t}\right)_{i+1}-\left(\frac{a}{t}\right)_i=0{,}01 \quad\Rightarrow\quad \frac{\lambda_{i+1}}{\lambda_i}=2 \qquad (2.3)$$

3. STRENGTH AND FRACTURE RISK ASSESSMENT OF TYPICAL STRUCTURAL ELEMENTS WITH DEFECTS UNDER STATIC LOADING

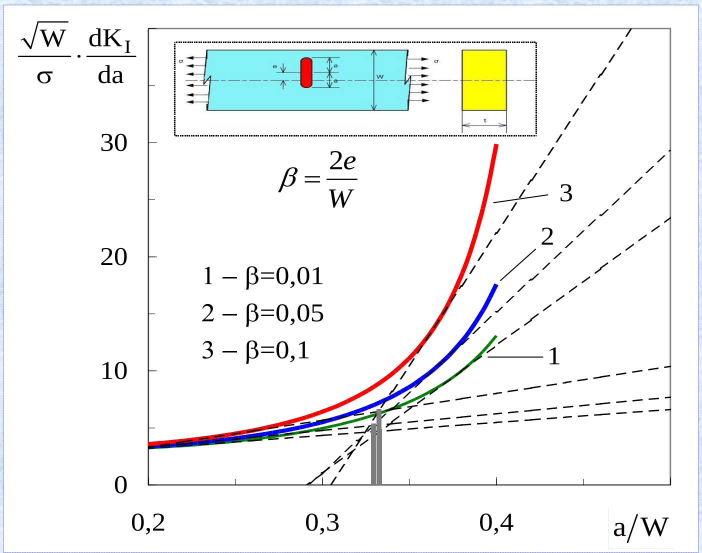
3.1. Sheets with through-thickness cracks



$1-(a/w)_* = 0.332$

$2-(a/w)_* = 0.316$

Fig. 3.1. Comparative assessment of danger of different crack-like defects in sheets: 1 – non-centered crack under uniform tension; 2 – two edge cracks under bending.



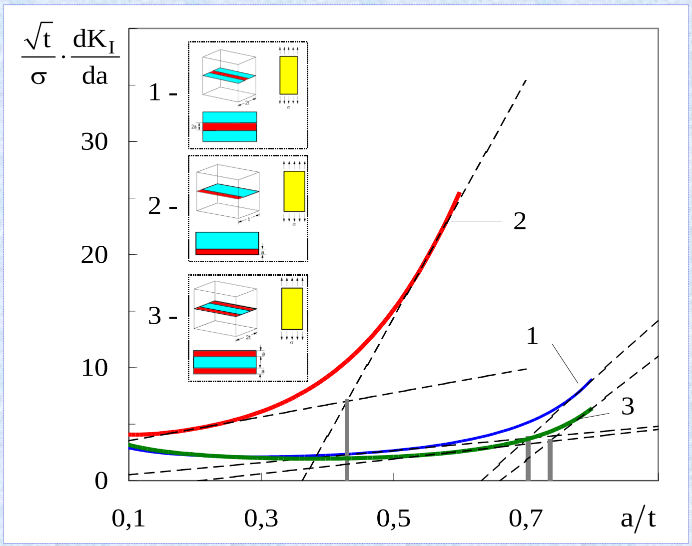
$1-(a/w)_* = 0.333$

$2-(a/w)_* = 0.329$

$3-(a/w)_* = 0.320$

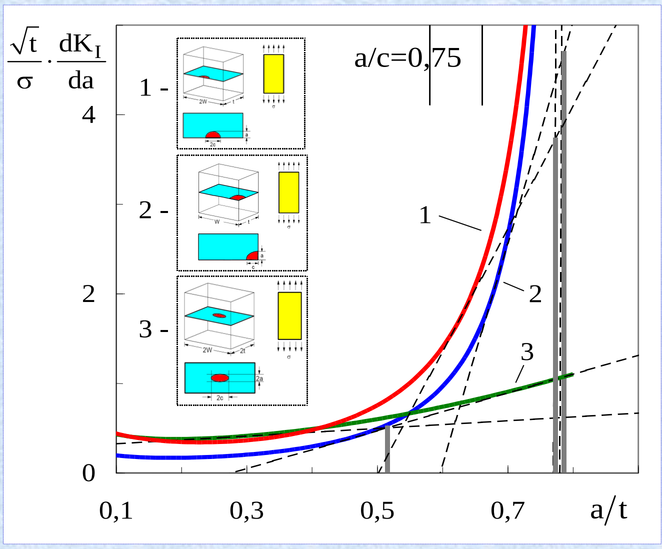
Fig. 3.2. Comparative assessment of danger of crack-like defects excentrically located in sheets: *1* – β = 0,01; *2* – β = 0,05; *3* – β = 0,1.

3.2. Plates with cracks of different shape



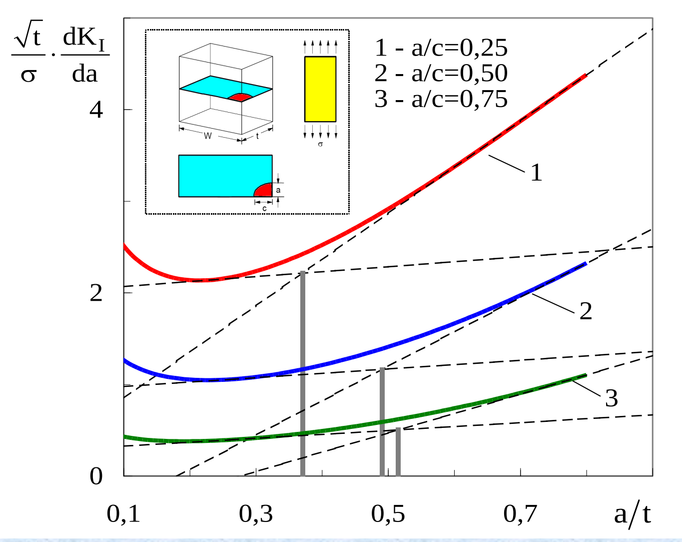
$1-(a/t)_* = 0.703$
$2-(a/t)_* = 0.429$
$3-(a/t)_* = 0.736$

Fig. 3.3. Comparative assessment of danger of crack-like defects in plates under uniform tension: 1 – extended centered through-thickness crack; 2 – extended surface crack; 3 – two extended surface crack.



$1-(a/t)_* = 0.769$
$2-(a/t)_* = 0.515$
$3-(a/t)_* = 0.747$

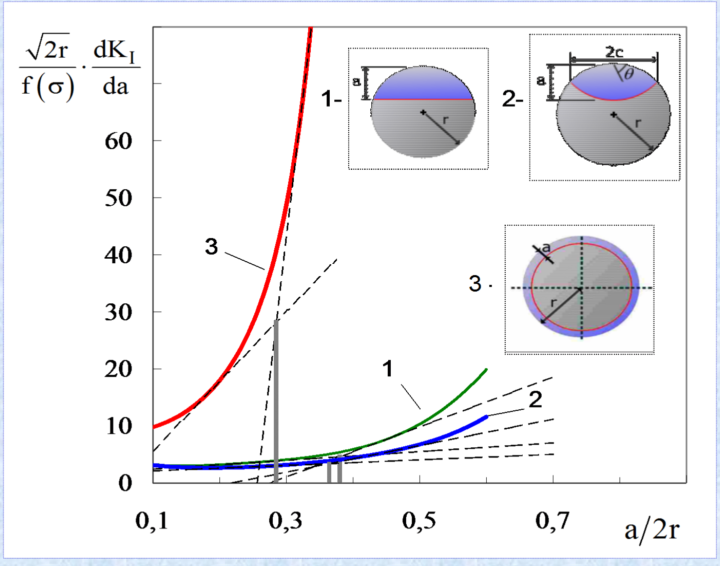
Fig. 3.4. Comparative assessment of danger of crack-like defects in plates under uniform tension: 1 – semielliptical surface crack; 2 – quarterelliptical corner crack; 3 – embedded elliptical crack.



$1-(a/t)_* = 0.370$
$2-(a/t)_* = 0.491$
$3-(a/t)_* = 0.515$

Fig. 3.5. Comparative assessment of danger of quarterelliptical corner cracks in plate under uniform tension: *1 –* a/c = 0,25; *2 –* a/c = 0,5; *3 –* a/c = 0,75.

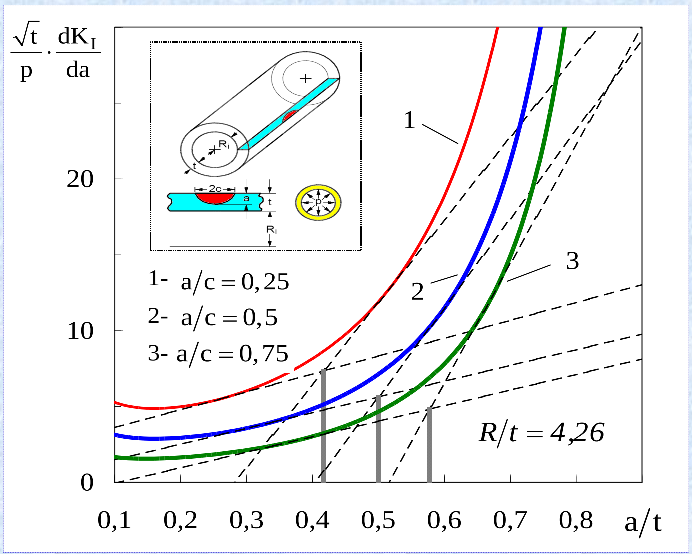
3.3. Bars with cracks of different shape



$1-(a/2r)_* = 0.380$
$2-(a/2r)_* = 0.364$
$3-(a/2r)_* = 0.285$

Fig. 3.6. Comparative assessment of danger of crack-like defects in bars under uniform tension: 1 – straight fronted crack; 2 – non-straight fronted crack; 3 – fully circumferential crack.

3.4. Pipelines with cracks

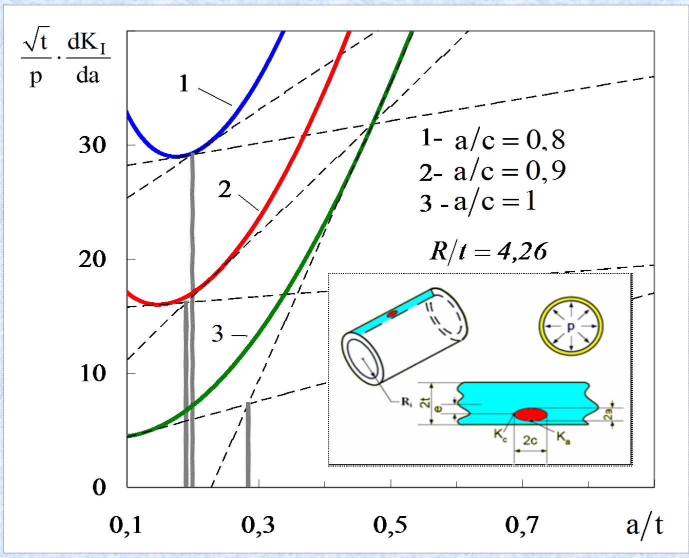


$1-(a/t)_* = 0.417$

$2-(a/t)_* = 0.501$

$3-(a/t)_* = 0.578$

Fig. 3.7. Comparative assessment of danger of external longitudinal semielliptical cracks of different shape in pipe under internal pressure: 1 – a/c=0.25; 2 –a/c=0.50; 3 – a/c=0.75.

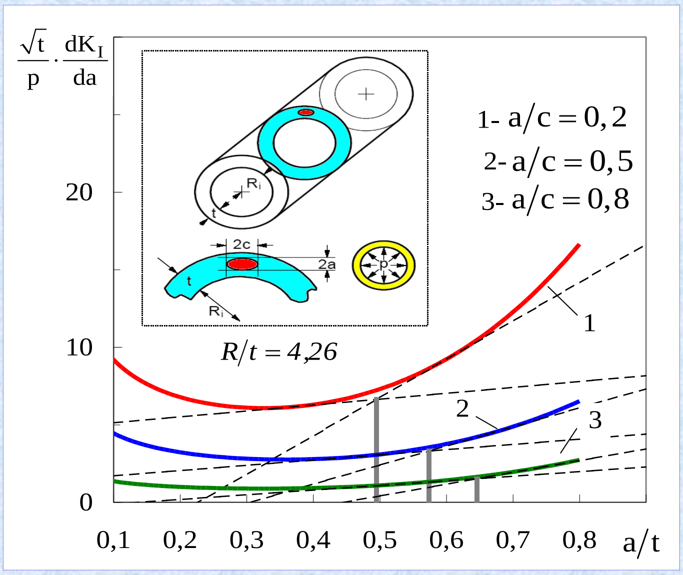


$1-(a/t)_* = 0.199$

$2-(a/t)_* = 0.189$

$3-(a/t)_* = 0.283$

Fig. 3.8. Comparative assessment of danger of longitudinal embedded elliptical cracks of different shape in pipe under internal pressure: 1 – a/c=0.8; 2 –a/c=0.9; 3 – a/c=1.0.

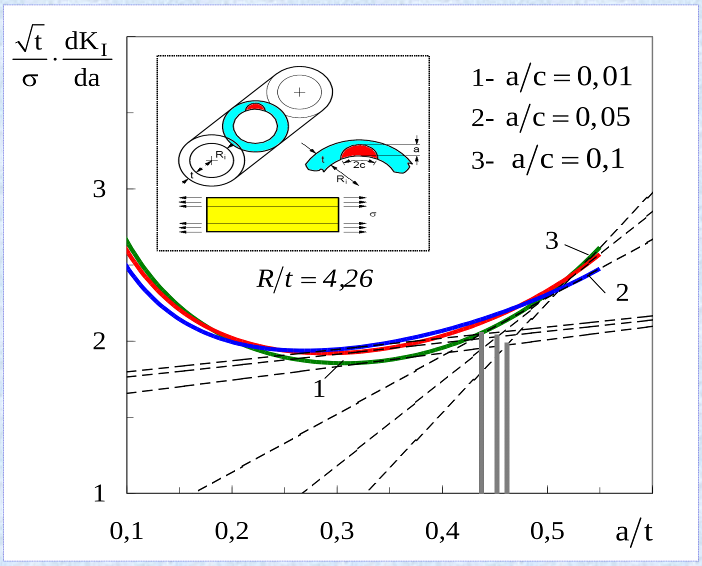


$1-(a/t)_* = 0.495$

$2-(a/t)_* = 0.574$

$3-(a/t)_* = 0.646$

Fig. 3.9. Comparative assessment of danger of circumferential embedded elliptical cracks of different shape in pipe under internal pressure: 1 – a/c=0.2; 2 –a/c=0.5; 3 – a/c=0.8.

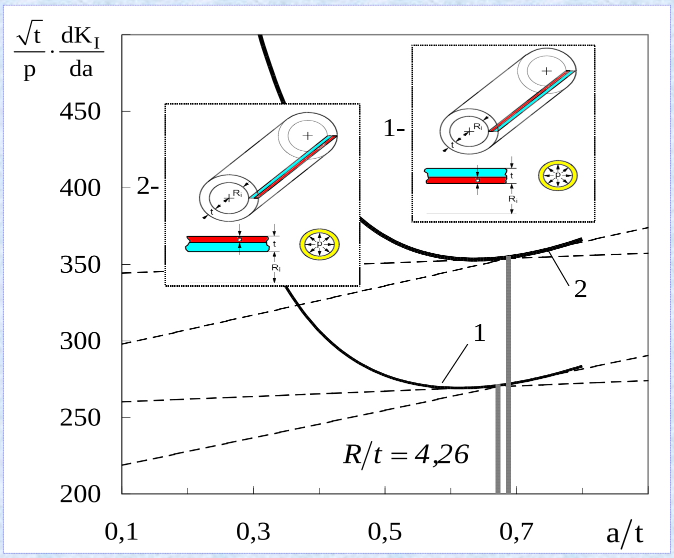


$1-(a/t)_* = 0.461$

$2-(a/t)_* = 0.452$

$3-(a/t)_* = 0.437$

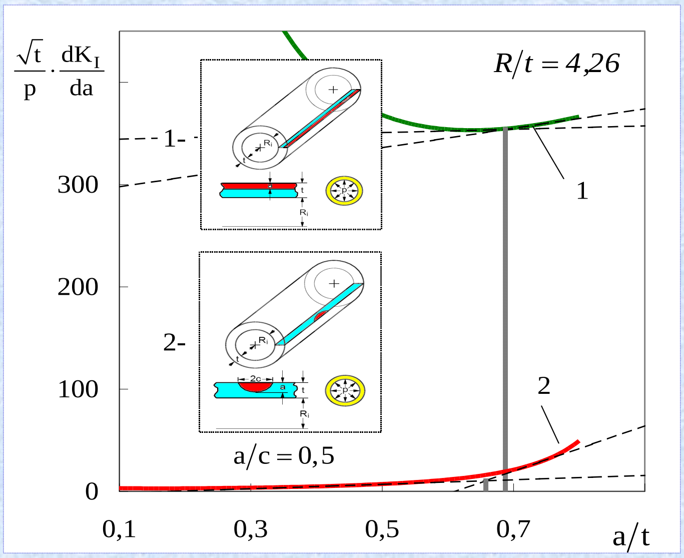
Fig. 3.10. Comparative assessment of danger of circumferential semielliptical cracks of different shape in pipe under axial loading: 1 – a/c=0.2; 2 –a/c=0.5; 3 – a/c=0.8.



$1-(a/t)_* = 0.672$

$2-(a/t)_* = 0.688$

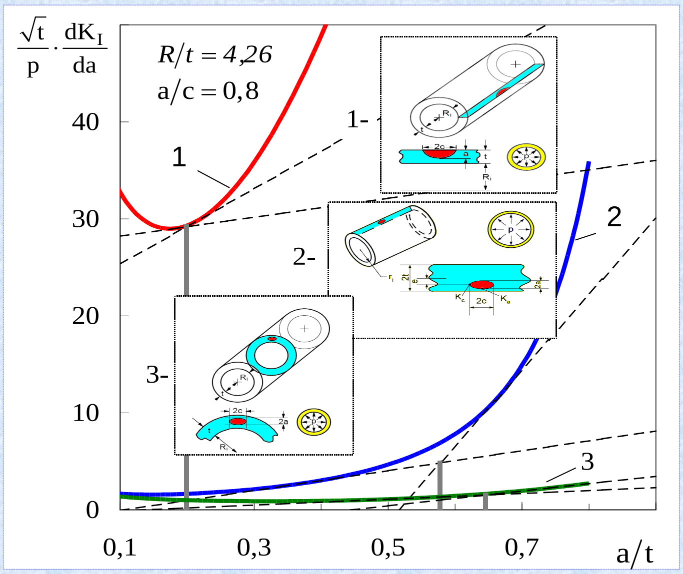
Fig. 3.11. Comparative assessment of danger of axial extended cracks in pipe: 1 – at internal surface; 2 – at external surface.



$1-(a/t)_* = 0.688$

$2-(a/t)_* = 0.658$

Fig. 3.12. Comparative assessment of danger of different axial cracks at external surface of pipe under internal pressure: 1 –extended crack; 2 – semielliptical crack.

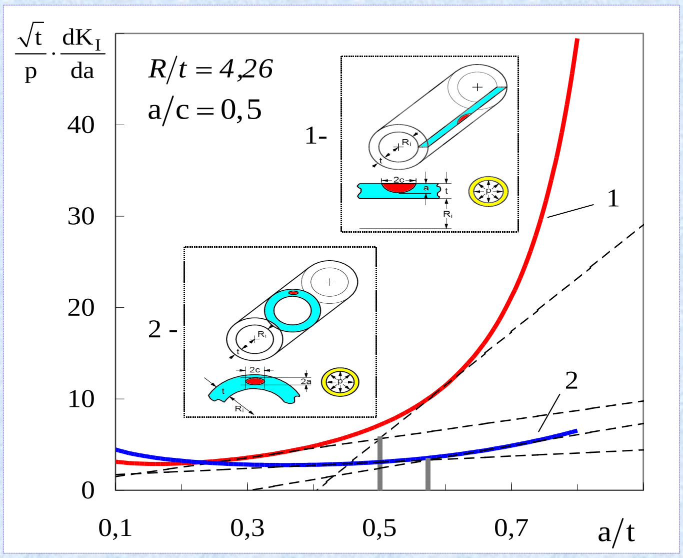


$1-(a/t)_* = 0.199$

$2-(a/t)_* = 0.578$

$3-(a/t)_* = 0.646$

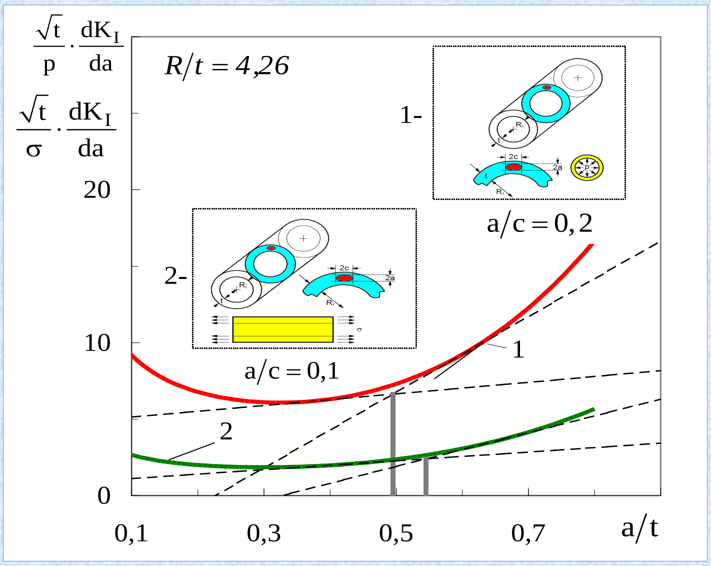
Fig. 3.13. Comparative assessment of danger of different cracks in pipe under internal pressure: 1 – axial semielliptical crack at external surface; 2 – axial embedded crack; 3 - circumferential embedded crack.



$1-(a/t)_* = 0.501$

$2-(a/t)_* = 0.574$

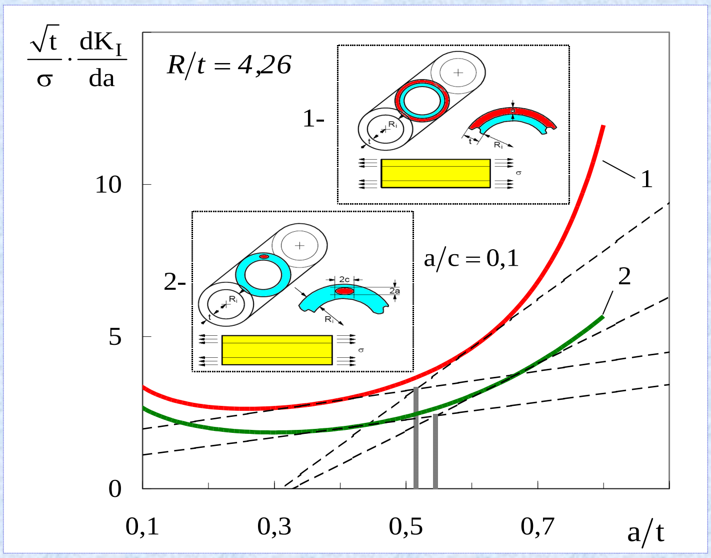
Fig. 3.14. Comparative assessment of danger of different cracks in pipe under internal pressure: 1 – axial semielliptical crack at external surface; 2 - circumferential embedded crack.



$1-(a/t)_* = 0.495$

$2-(a/t)_* = 0.545$

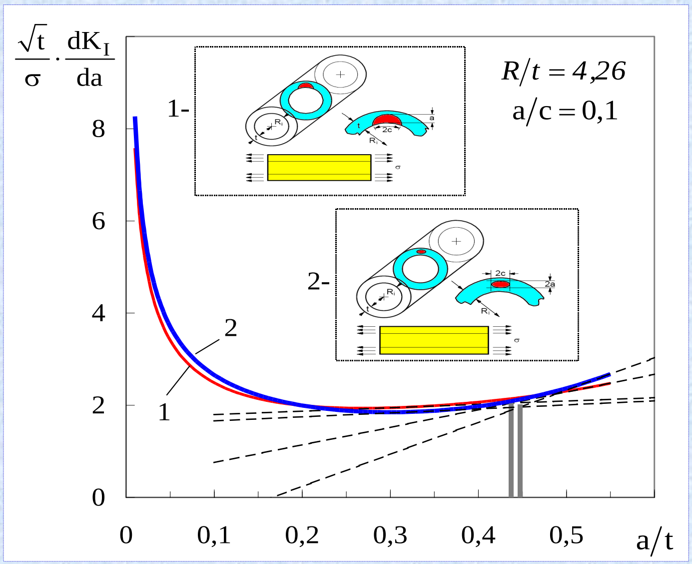
Fig. 3.15. Comparative assessment of danger of circumferential embedded crack in pipe : 1 – under internal pressure; 2 – under axial loading.



$1-(a/t)_* = 0.516$

$2-(a/t)_* = 0.545$

Fig. 3.16. Comparative assessment of danger of cracks in pipe under axial loading: 1 – fully circumferential crack; 2 - circumferential embedded crack.

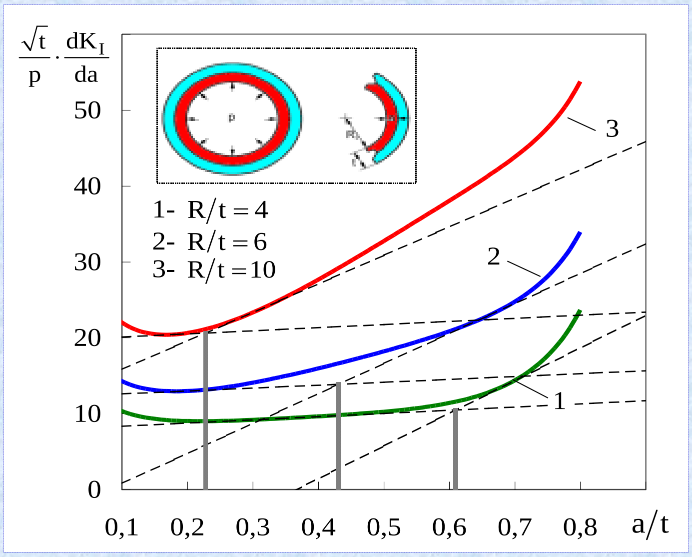


$1-(a/t)_* = 0.437$

$2-(a/t)_* = 0.448$

Fig. 3.17. Comparative assessment of danger of circumferential cracks in pipe under axial loading: 1 – semielliptical crack; 2 - embedded crack.

3.5. Spherical shells with cracks

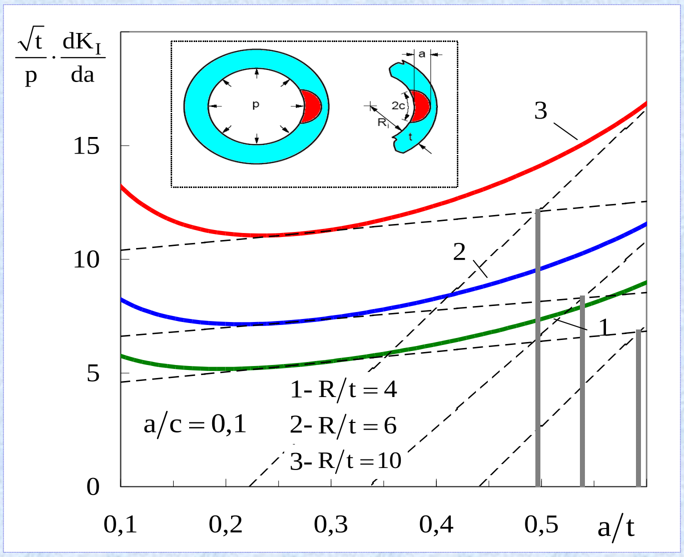


$1-(a/t)_* = 0.610$

$2-(a/t)_* = 0.431$

$3-(a/t)_* = 0.228$

Fig. 3.18. Effect of size of spherical shell on danger of fully circumferential internal cracks under internal pressure: 1 – R/t = 4; 2 - R/t = 6; R/t = 10.

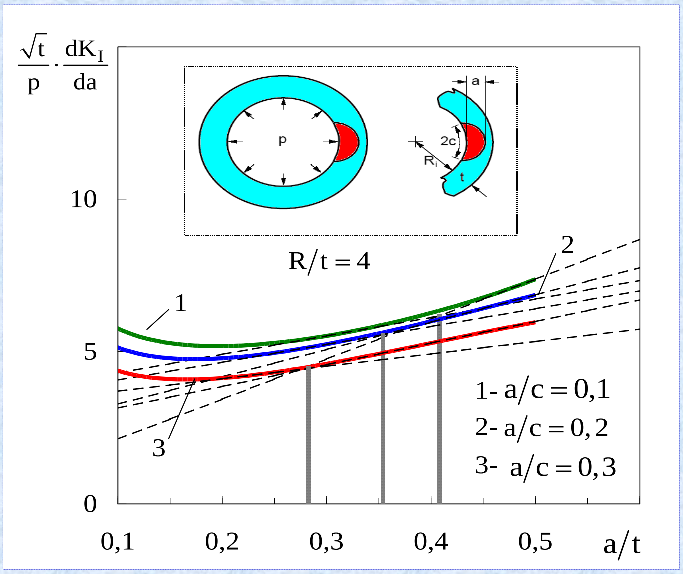


$1-(a/t)_* = 0.592$

$2-(a/t)_* = 0.539$

$3-(a/t)_* = 0.497$

Fig. 3.19. Effect of size of spherical shell on danger of internal semielliptical cracks under internal pressure: 1 – R/t = 4; 2 - R/t = 6; R/t = 10.

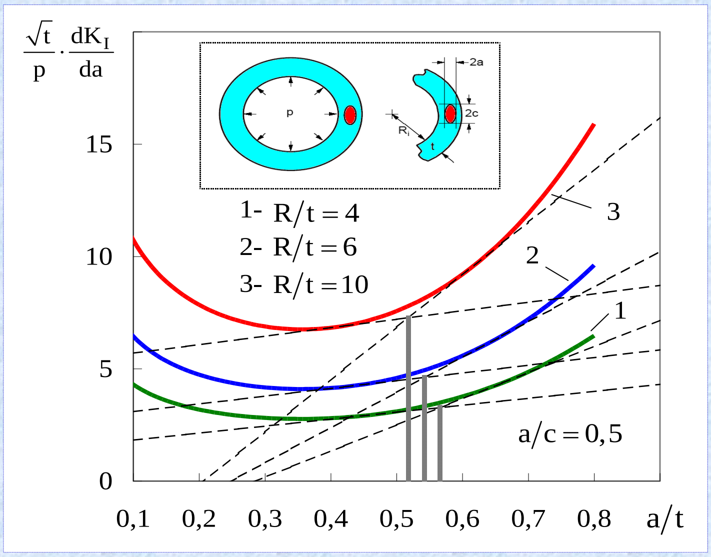


$1-(a/t)_* = 0.408$

$2-(a/t)_* = 0.354$

$3-(a/t)_* = 0.283$

Fig. 3.20. Comparative assessment of danger of internal semielliptical cracks of different shape in spherical shell under internal pressure: 1 – a/c = 0.1; 2 - a/c = 0.2; a/c = 0.3.

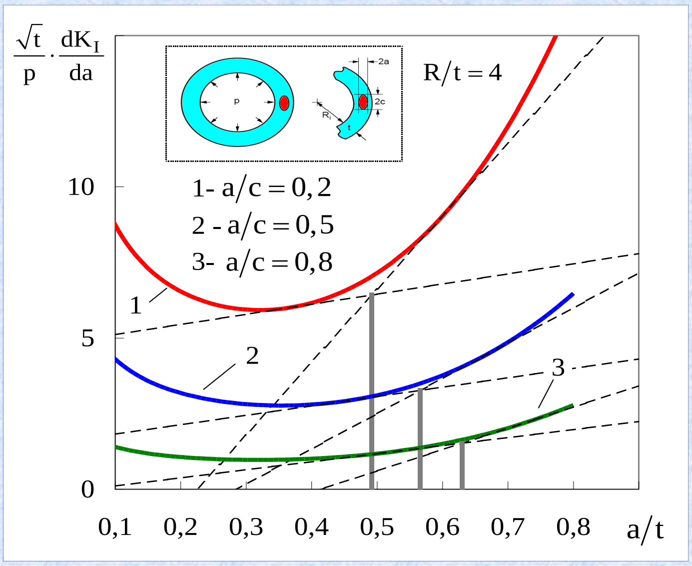


$1-(a/t)_* = 0.546$

$2-(a/t)_* = 0.542$

$3-(a/t)_* = 0.518$

Fig. 3.21. Effect of size of spherical shell on danger of embedded cracks under internal pressure: 1 – R/t = 4; 2 - R/t = 6; R/t = 10.

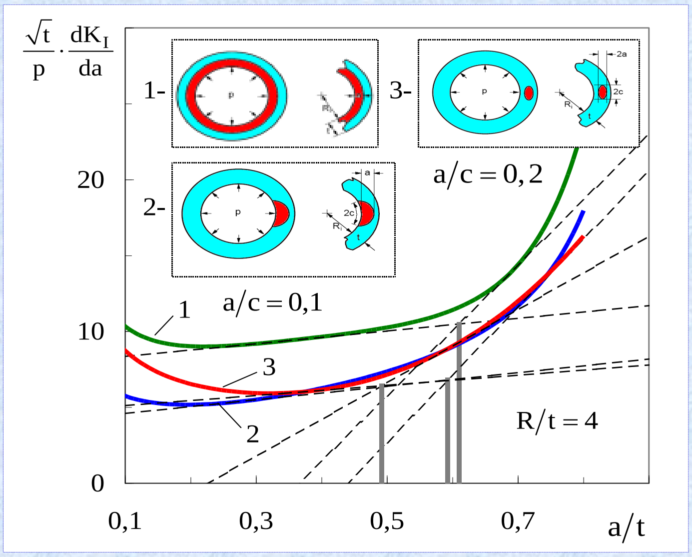


$1-(a/t)_* = 0.492$

$2-(a/t)_* = 0.566$

$3-(a/t)_* = 0.630$

Fig. 3.22. Comparative assessment of danger of embedded cracks of different shape in spherical shell under internal pressure: 1 – a/c = 0.2; 2 - a/c = 0.5; a/c = 0.8.



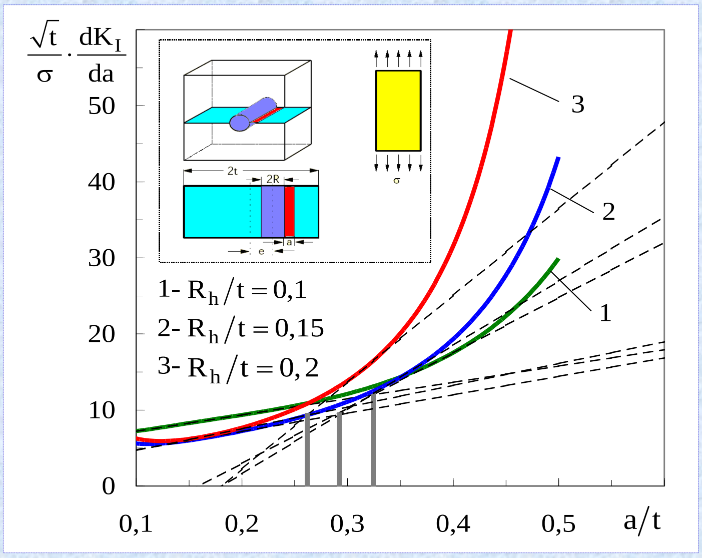
$1-(a/t)_* = 0.610$

$2-(a/t)_* = 0.592$

$3-(a/t)_* = 0.492$

Fig. 3.23. Comparative assessment of danger of fully circumferential crack (1), embedded crack (2) and semielliptical crack (3) in spherical shell under internal pressure.

3.6. Assessment of cracks danger at holes in structural elements of different shape

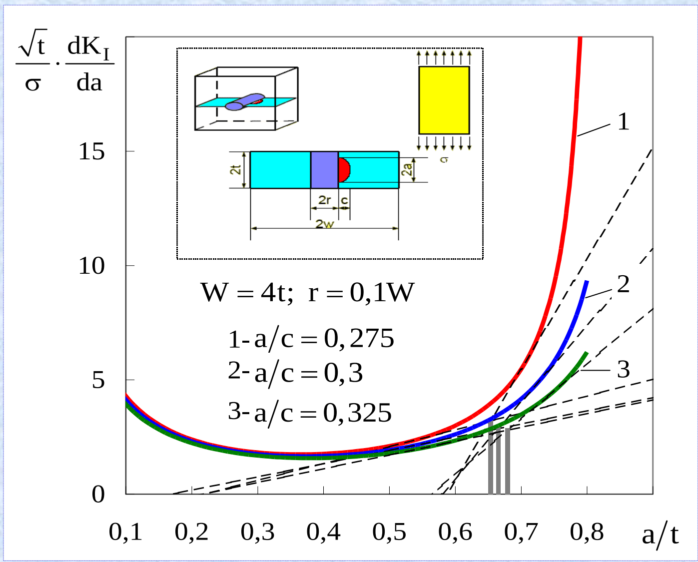


$1-(a/t)_* = 0.324$

$2-(a/t)_* = 0.292$

$3-(a/t)_* = 0.262$

Fig. 3.24. Effect of size of hole on danger of single crack from hole in plate under uniform tension: 1 – R/t = 0,10; 2 - R/t = 0,15; R/t = 0,20.

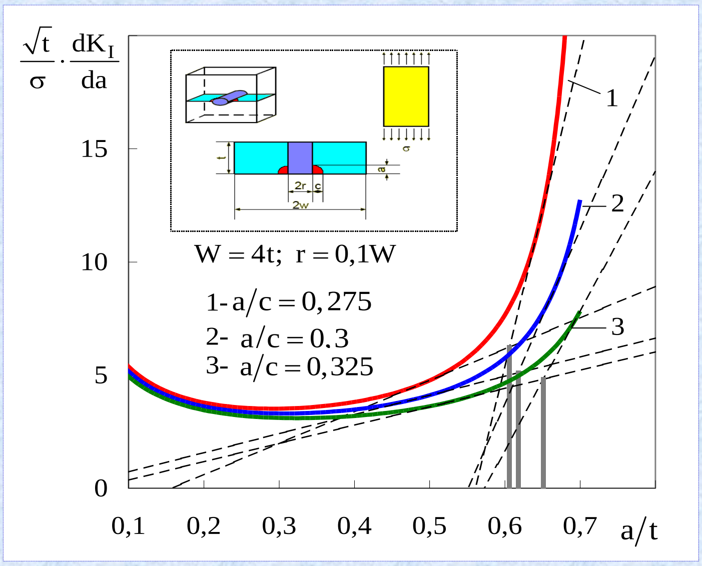


$1-(a/t)_{*}=0.649$

$2-(a/t)_{*}=0.665$

$3-(a/t)_{*}=0.679$

Fig. 3.25. Comparative assessment of danger of single semielliptical crack of different shape from hole in plate under uniform tension: 1 – a/c = 0.275; 2 - a/c = 0.300; a/c = 0.325.

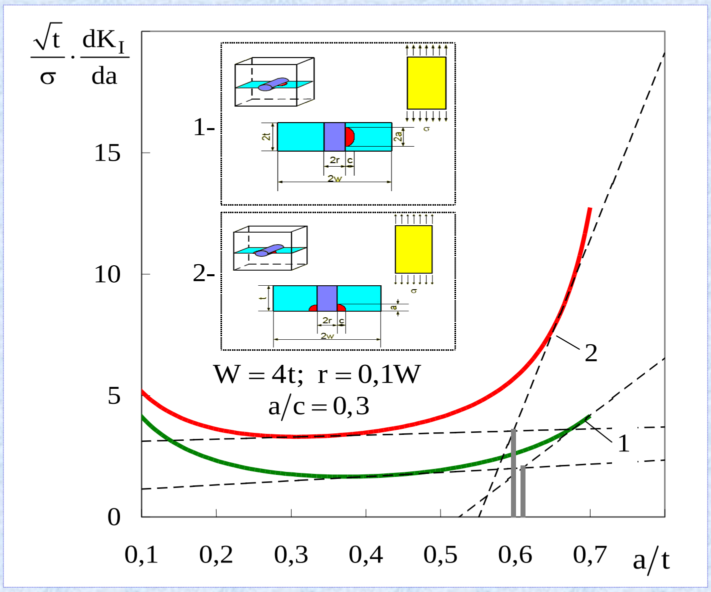


$1-(a/t)_{*}=0.606$

$2-(a/t)_{*}=0.618$

$3-(a/t)_{*}=0.651$

Fig. 3.26. Comparative assessment of danger of two quarterelliptical cracks of different shape from hole in plate under uniform tension: 1 – a/c = 0.275; 2 - a/c = 0.300; a/c = 0.325.



$1-(a/t)_* = 0.665$

$2-(a/t)_* = 0.618$

Fig. 3.27. Comparative assessment of danger of cracks of different shape from hole in plate under uniform tension:
1 – single semielliptical crack; 2 - two quarterelliptical cracks.

4. DURABILITY ASSESSMENT OF DEFECTED STRUCTURAL ELEMENTS UNDER CYCLIC LOADING IN OPERATING ENVIRONMENTS

Comparative assessment of residual durability of structural element with defect was made grounding on the following relations:

$$N_{fc} = \int_{a_{th}}^{a_{fc}} \frac{da}{F(\Delta K_I)} \quad \text{and} \quad N_* = \int_{a_{th}}^{a_*} \frac{da}{F(\Delta K_I)} \qquad (4.1)$$

N_{fc} *and* N_* - number cycles of loading to failure of structural element;

$F(\Delta K_I)$ - known function of stress intensity factor, which describes fatigue crack growth rate in given material under given operating conditions;

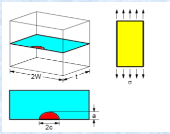
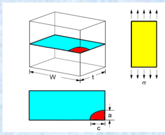
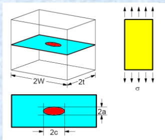
a_{th} - threshold defect size;

a_{fc} - critical defect size;

a_* - characteristic (specific) defect size.

4.1. Durability of plates with cracks of different shape

Table 4.1.

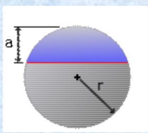
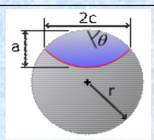
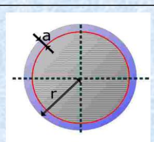
Plates with Defects	a_{th} mm	a_* mm	a_{fc} mm	N_* thousands cycles	N_{fc} thousands cycles
 $a/c = 0.75$	12.08	61.52	20.74	-	997.2
 $a/c = 0.75$	10.36	41.20	17.77	-	**892.0**
 $a/c = 0.75$	13.46	29.88	22.02	-	1105.6

Steel 20; t=40 mm; W=400 mm; R=0; f=0.1Hz; $\Delta\sigma = 0.5\sigma_{0.2} = 135MPa$

Environment : $H_2O + NH_3\ (pH = 9.0)$

4.2. Influence of cracks shape on durability of bars

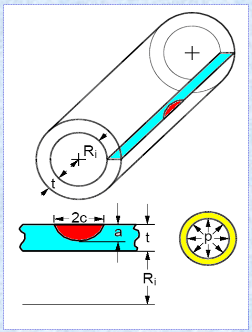
Table 4.2.

Bars with Defects	a_{th} mm	a_* mm	a_{fc} mm	N_* thousands cycles	N_{fc} thousands cycles
	9.68	15.20	32.00	3169.70	4896.80
	1.62	14.56	5.96	–	189.45
	1.00	11.40	2.55	–	**35.10**

Steel 12Kh1MF; r=40 mm; R=0; f=0.1Hz; $\Delta\sigma = 0.5\sigma_{0.2} = 13MPa$

Environment : $H_2O + NH_3\ (pH = 9.0) + 100\,mg/kg\ N_2H_4$

4.3. Durability assessment of pipes with defects of different shape and location

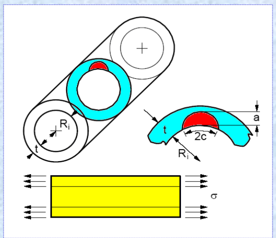


Scheme of defected pipe

Table 4.3.

Shape of defect	$C_{H(v)}$, ppm	a_{th} mm	a_* mm	a_{fc} mm	N_* thousands cycles	N_{fc} thousands cycles
$a/c = 0.25$	1.97	10.38	20.85	24.20	260.67	266.58
	2.07	10.38	20.85	23.41	253.51	257.46
	2.20	11.56	20.85	22.62	213.77	216.01
	2.47	10.77	20.85	21.04	194.27	194.45
	2.68	10.77	20.85	20.65	-	183.22
$a/c = 0.50$	1.97	12.35	20.85	27.76	313.39	317.54
	2.07	12.75	20.85	26.97	268.07	270.62
	2.20	13.93	20.85	25.78	237.20	238.03
	2.47	13.14	20.85	24.60	-	205.65
	2.68	12.75	20.85	24.20	-	228.79
$a/c = 0.75$	1.97	14.72	20.85	30.92	345.29	348.02
	2.07	15.12	20.85	30.13	298.81	300.24
	2.20	16.70	20.85	28.94	238.52	238.56
	2.47	15.51	20.85	27.36	-	233.38
	2.68	15.51	20.85	27.36	-	233.38

Steel 16HS; Pipe: D=526 mm, t=50 mm; p=70 bars; R=0; f=0.1Hz.
$C_{H(v)}$ – hydrogen concentration in bulk of metal

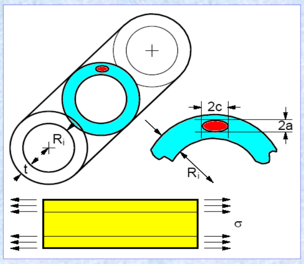


Scheme of defected pipe

Table 4.4.

Shape of defect	$C_{H(v)}$, ppm	a_{th} mm	a_* mm	a_{fc} mm	N_* thousands cycles	N_{fc} thousands cycles
$a/c = 0.01$	1.97	15.74	23.05	40.00	438.36	638.37
	2.07	15.98	23.05	40.00	417.72	600.29
	2.20	18.78	23.05	39.36	291.53	504.58
	2.47	16.72	23.05	37.50	354.43	483.21
	2.68	16.52	23.05	37.20	355.29	475.52
$a/c = 0.05$	1.97	15.64	22.60	40.00	421.07	632.32
	2.07	15.89	22.60	40.00	400.44	593.45
	2.20	18.63	22.60	40.00	272.75	499.17
	2.47	16.62	22.60	38.03	337.31	474.21
	2.68	16.43	22.60	37.69	338.99	466.78
$a/c = 0.10$	1.97	15.69	21.85	40.00	386.68	625.32
	2.07	15.94	21.85	40.00	366.58	585.74
	2.20	18.53	21.85	40.00	241.33	502.70
	2.47	16.62	21.85	38.87	310.34	469.68
	2.68	16.43	21.85	38.52	313.55	462.46

Steel 16HS; Pipe: D=526 mm, t=50 mm; R=0; f=0.1Hz. $\sigma = 50MPa$
$C_{H(v)}$ – hydrogen concentration in bulk of metal

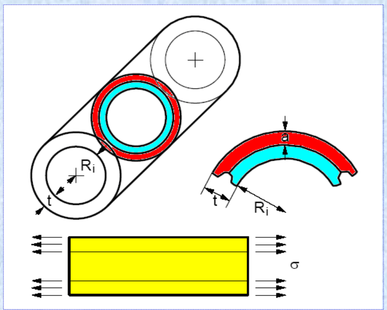


Scheme of defected pipe

Table 4.5.

Shape of defect	$C_{H(v)}$, ppm	a_{th} mm	a_* mm	a_{fc} mm	N_* thousands cycles	N_{fc} thousands cycles
$a/c=0.05$	1.97	13.98	26.30	40.00	527.30	600.65
	2.07	14.22	26.30	39.36	498.55	560.86
	2.20	16.77	26.30	37.69	414.81	473.17
	2.47	14.91	26.30	35.34	413.60	446.00
	2.68	14.71	26.30	35.00	**410.40**	440.12
$a/c=0.10$	1.97	14.37	27.25	40.00	548.20	620.58
	2.07	14.61	27.25	40.00	519.16	581.33
	2.20	17.26	27.25	38.82	432.28	490.82
	2.47	15.35	27.25	36.47	428.33	460.82
	2.68	15.10	27.25	36.07	429.08	458.83
$a/c=0.25$	1.97	16.18	31.10	40.00	623.84	686.89
	2.07	16.43	31.10	40.00	593.80	648.40
	2.20	19.46	31.10	40.00	491.99	545.37
	2.47	17.26	31.10	40.00	489.73	521.02
	2.68	17.01	31.10	40.00	487.14	516.14

Steel 16HS; Pipe: D=526 mm, t=50 mm; R=0; f=0.1Hz. $\sigma=50MPa$
$C_{H(v)}$ *– hydrogen concentration in bulk of metal*



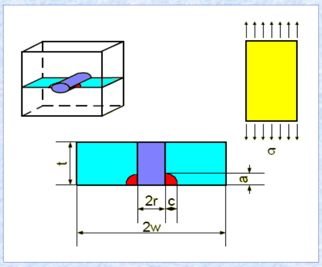
Scheme of defected pipe

Table 4.6.

$C_{H(v)}$, ppm	a_{th} mm	a_* mm	a_{fc} mm	N_* thousands cycles	N_{fc} thousands cycles
1.97	10.79	25.80	36.27	472.20	503.01
2.07	11.28	25.80	34.80	415.13	439.11
2.20	13.24	25.80	32.84	360.55	378.70
2.47	11.77	25.80	30.88	**334.68**	343.58
2.68	11.28	25.80	30.39	361.54	369.31

Steel 16HS; Pipe: D=526 mm, t=50 mm; R=0; f=0.1Hz. $\sigma=50MPa$
$C_{H(v)}$ *– hydrogen concentration in bulk of metal*

4.4. Durability of defected structural elements with holes



Scheme of defected element

Table 4.7.

Shape of defect	Environment	a_{th} mm	a_* mm	a_{fc} mm	N_* thousands cycles	N_{fc} thousands cycles
$a/c=0.275$	1	5.75	9.09	10.80	1432.40	1488.10
	2	8.43	9.09	10.80	384.66	540.79
	3	0.50	9.09	3.38	–	**38.24**
	4	2.15	9.09	8.84	–	1115.42
$a/c=0.300$	1	5.86	9.27	10.80	1534.97	1621.20
	2	8.74	9.27	10.80	377.35	661.81
	3	0.50	9.27	3.28	–	**37.83**
	4	2.15	9.27	9.26	–	1075.25
$a/c=0.3250$	1	5.96	9.77	10.80	1662.11	1733.72
	2	9.15	9.77	10.80	402.20	648.03
	3	0.50	9.77	3.28	–	**38.15**
	4	2.05	9.77	9.67	–	1146.91

Steel 08Kh18N12T; t=15 mm; 2W=120 mm; 2r=6mm; R=0; f=0.1Hz; $\Delta\sigma = 0.5\sigma_{0.2} = 150 MPa$

Environment

$1 - Air;$

$2 - H_2O + NH_3\,(pH = 9.0);$

$3 - H_2O + NH_3(pH = 9) + 100\, mg/kg\ N_2H_4;$

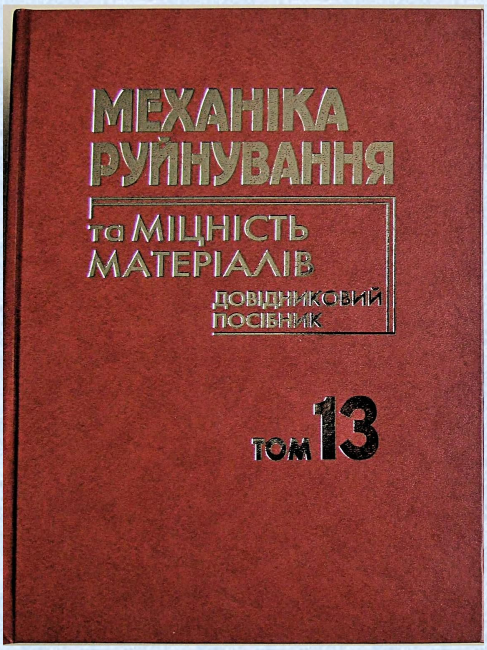
$4 - H_2O + NH_3(pH = 9) + 100\, \mu g/kg\ N_2H_4.$

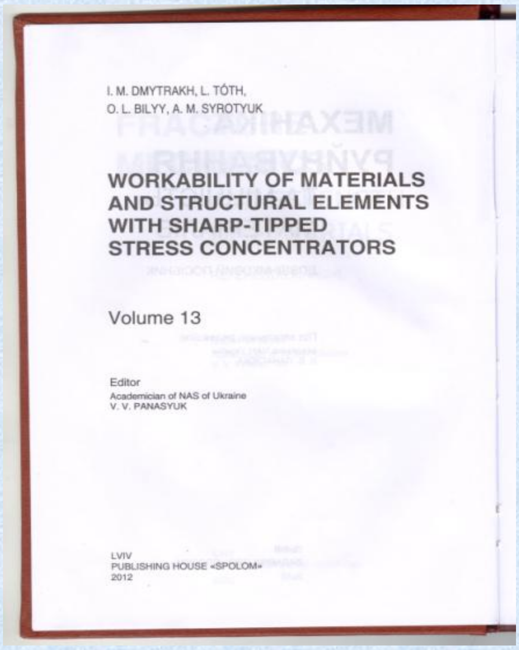
5. CONCLUSIONS

1. The strength and durability assessment of structures with crack-like defects are presented based on the concept of index of structural element resistance to crack growth. This index is a characteristic of the stress intensity factor rate at the crack tip during its propagation in a considered structural element. The most typical structural elements (sheets, plates, bars, cylindrical shells, etc.) with defects of different shape and location were considered.

2. The examples of residual lifetime and fracture risk assessment of defected structural components with the account of operation factors (loading mode, influence of environments, material state) are demonstrated.

3. The received data may be used in the field of design, technical diagnostics and operation of the critical structures in different branches of industry (mechanical engineering, power generation industry, pipeline transport, etc.).

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WORKABILITY OF MATERIALS
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WITH SHARP-TIPPED
STRESS CONCENTRATORS

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Thank you for your attention!