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THE ROLE OF NDT IN FRACTURE MECHANICS AND STRUCTURAL INTEGRITY ANALYSIS

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Abstract

- The review of non-destructive testing of a pressure vessel for compressed air is given, as well as the assessment and analysis of defects on the integrity of the vessel itself. The focus here is on welded joints, as the most critical areas in pressure vessels, especially if thickness is large, like in the case considered here (50 mm), cylindrical air storage vessels made of HSLA steel
- Toward this end conventional NDT methods, such as UT and Radiography are used in the first phase of this research, providing valuable data for structural integrity assessment based on detected unacceptable defects in welded joints. Anyhow, since few unacceptable defects were found by conventional UT, there was a need to use advanced NDT UT methods, such as Phased Array Ultrasonic Testing (PAUT) and Time of Flight Diffraction (TOFD), to evaluate defect position and size more precisely.
- In this way risk of failure can be assessed more reliable, which is of utmost importance for pressure vessel where probability of failure is low, but the consequence of failure is potentially catastrophic, like in the case considered here.

Introduction

- Welded joints are the ‘weakest’ location in a structure, in respect to defects, so the detection of defects in welded joints is of utmost importance. NDT by UT techniques are used for long time to show if a structure is safe during its exploitation. In addition to conventional UT, two new, advanced UT methods have been recently used for testing: Phased Array UT method (PAUT). All of these tests are performed in accordance with relevant standards
- Assessing the integrity of pressure equipment is a very responsible job. Analysis of critical defects using methods of fracture mechanics will be given in this paper. The review of non-destructive testing of pressure vessel for compressed air will follow.

- PAUT is the newest and most advanced method of ultrasonic testing. The PAUT probe usually consists of eight small ultrasonic transducers, and each can be independently pulsed. By making the pulse delay from each transducer in the timely manner, a pattern of constructive interference is set up. To be more precise, by changing the progressive time delay, the beam can be steered electronically, and the data from those beams can be put together to make a visual image that shows a slice through the object. PAUT tests was also performed for all welded joints (100% scale), in accordance with the acceptance criteria as defined by the corresponding standard. During ultrasonic inspection, several defects are noticed in certain welded joints.
- Phased Array Ultrasonic Technique (PAUT) method of ultrasonic testing is used in this particular case due to its accuracy and sensitivity to confirm previous defect indications and to indicate new ones which was not possible to detect with conventional UT.

Non destructive testing of pressure vessel

- The inspection and assessment of pressure equipment is performed according to the PED Directive 2014/14 / EU, and according to the standard EN 13445: 2015. In the further discussion, specific cases will be considered, and these are pressure vessels that belong to the Reversible Hydropower Plant "BAJINA BAŠTA.
- Inspection and testing of vessels under pressure, was performed by advanced NDT methods, which have a wide application in all areas of industry, not only in pressure equipment. For internal errors, the ultrasound method according to the standard SRPS EN ISO 11666: 2018/ was applied. In general, ultrasonic testing is mostly used in the testing of pressure equipment, which in this case proved to be the most reliable technique in detecting errors. An analysis of the results of the advanced NDT methods applied to these vessels will be discussed

Conventional UT testing

After the final conventional UT testing of all vessels, 3 of them arechosen for more detailed analysis:

- PV 977 with defect 2.5 (length 2c=170 mm, depth a=14 mm, 28-42 mm along the thickness of the mid-circular joint),
- PV 971 - defect 1.1 (length 2c=180 mm, depth a=32 mm, 18-50 mm along the thickness, circular seam with the bottom cover) and
- 970 - defect 5.6 (length 2c=75 mm, depth a=20 mm, positioned along the thickness from 18 to 38 mm, in a longitudinal joint).

One should notice that there is no residual stresses in these PVs due to Post-Weld-Heat-Treatment (PWHT), while the material properties are as follows:

- Fracture toughness K_{Ic} for the weld metal is taken as 1580 MPa√mm in all cases, being the minimum value (in HAZ), as shown in [16].
- Collapse stress σ_c taken as the mid-value between *YS*=500 MPa, *TS*=650 MPa.

Introduction to Fracture Mechanics

- Practical application of fracture mechanics is based on twofold interpretation of its parameters: on one hand, they represent loading and structural geometry, and on the other they represent material properties and its resistance to crack growth.
- In that way the triangle of fracture mechanics has been established, Fig. 1, enabling fracture mechanics to become one of the foundations of a new discipline – structural integrity. Thus, instead of only handling fracture analysis, fracture mechanics has become an important tool in the hands of engineers whose job is to prevent fracture.

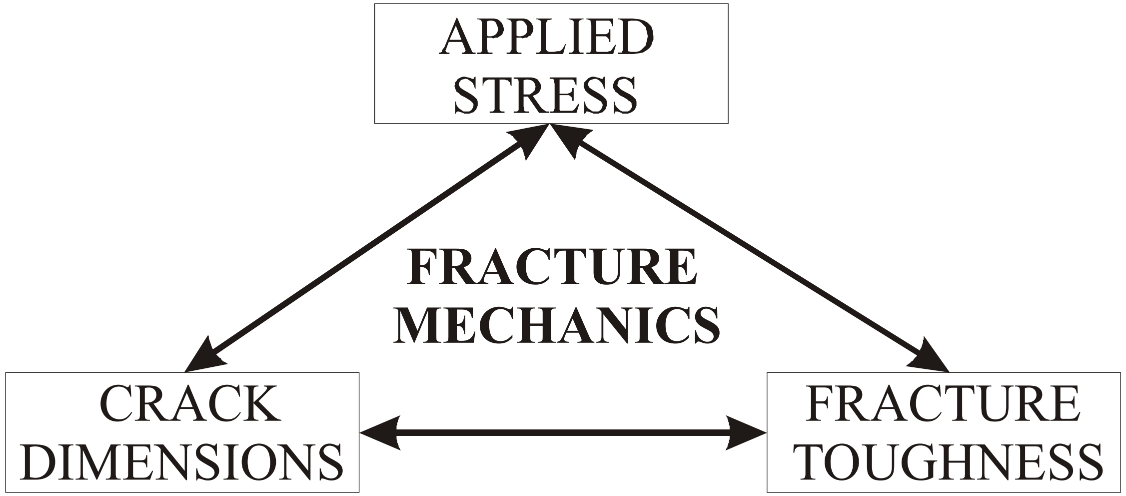


Figure 1. Fracture mechanics triangle

Introduction to Structural Integrity

- Fracture mechanics has brought significant changes in engineering practice. As an example to illustrate this statement, the problem with the Alaska pipeline and application of the fracture-safe principle in design may be mentioned. In case of the pipeline from Alaska to the rest of the USA, the fracture mechanics criteria were adopted instead of traditional standards on admissible defects in a welded joint.
- Namely, when non-destructive testing revealed a large number of defects in round welded joints which, according to the then effective standards, should have been repaired, the question of economic justification, i.e. necessity of repair, arose.

Application of linear elastic fracture mechanics

- The application of LEFM is based on the stress intensity factor, K_{I}, which on one hand represents loading and structural geometry, including crack dimensions, and on the other, its critical value, $K_{\mathrm{I}c}$, represents the material property. Based on this interpretation of LEFM parameters and Griffith's energy criterion, one can establish simple dependencies for the assessment of structural integrity.

$K_{\mathrm{I}} \leq K_{\mathrm{I}c}$ – structural integrity is not jeopardized

$K_{\mathrm{I}} > K_{\mathrm{I}c}$ - structural integrity is threatening due to possibility of brittle fracture

Application of elastic plastic fracture mechanics

- There are few ways to take into account material plasticity in assessment of structural integrity, all of which are based on application of crack tip opening displacement or J integral, as appropriate parameters of elastic-plastic fracture mechanics.
- Crack tip opening displacement (CTOD), although without clear theoretical base, has a wide practical application, mainly due to the simplicity of determination. On the other hand, the J integral requires a more complex procedure for determination, but as an energy parameter based on fundamental laws of continuum mechanics has equally important practical application.

Failure analysis diagram

Structures made of ductile materials are less susceptible to brittle fracture, and therefore may fracture by plastic collapse. The mechanism of plastic collapse is not covered by designed CTOD curve, so its analysis requires a more general, two-parameter approach, realized through the Failure Analysis Diagram (FAD). This diagram represents the boundary curve, constructed according to the modified model of a yielding strip for a passing-through crack on an infinite plate:

$$\frac{K_{eff}}{K_{\mathrm{I}}} = \frac{\sigma_c}{\sigma}\left[\frac{8}{\pi^2}\ln\sec\frac{\pi}{2}\frac{\sigma}{\sigma_c}\right]^{1/2}$$

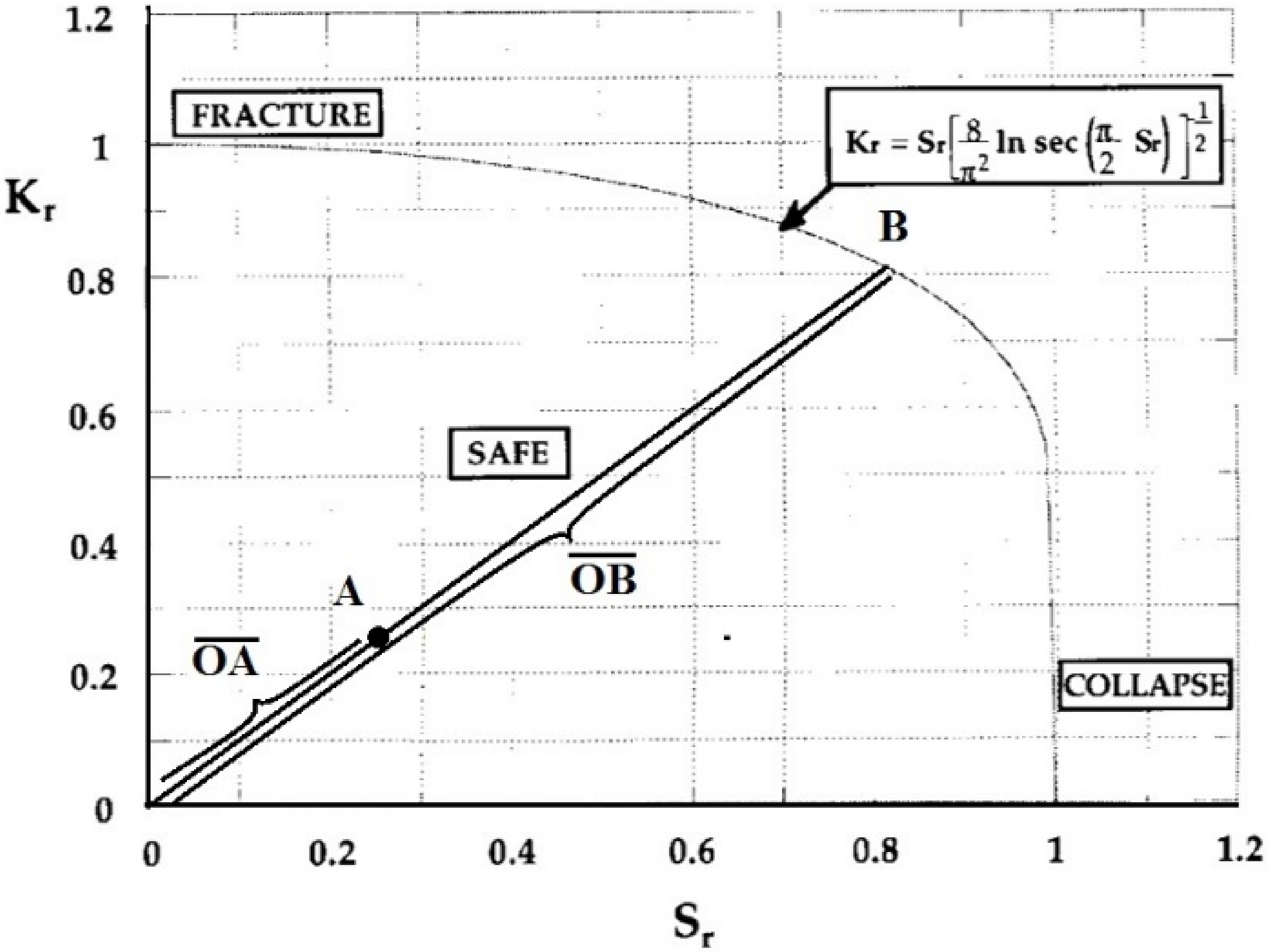
where $K_{\mathrm{I}} = \sigma\sqrt{\pi a}$, K_{eff} was introduced instead of δ ($K_{eff}^2 = \delta\sigma_Y E$), and yield stress σ_Y was replaced by plastic collapse stress σ_c as a more convenient yield criterion for actual structures. As a final step, non-dimensional variables $S_r = \sigma/\sigma_c$ and $K_r = K_{\mathrm{I}}/K_{\mathrm{I}c}$ are defined, where it is supposed that K_{eff} equals to the fracture toughness of the material, so that Eq. (4) becomes:

Failure analysis diagram

$$K_r = S_r\left[\frac{8}{\pi^2}\ln\sec\left(\frac{\pi}{2}S_r\right)\right]^{-1/2}$$

Failure Assessment Diagram

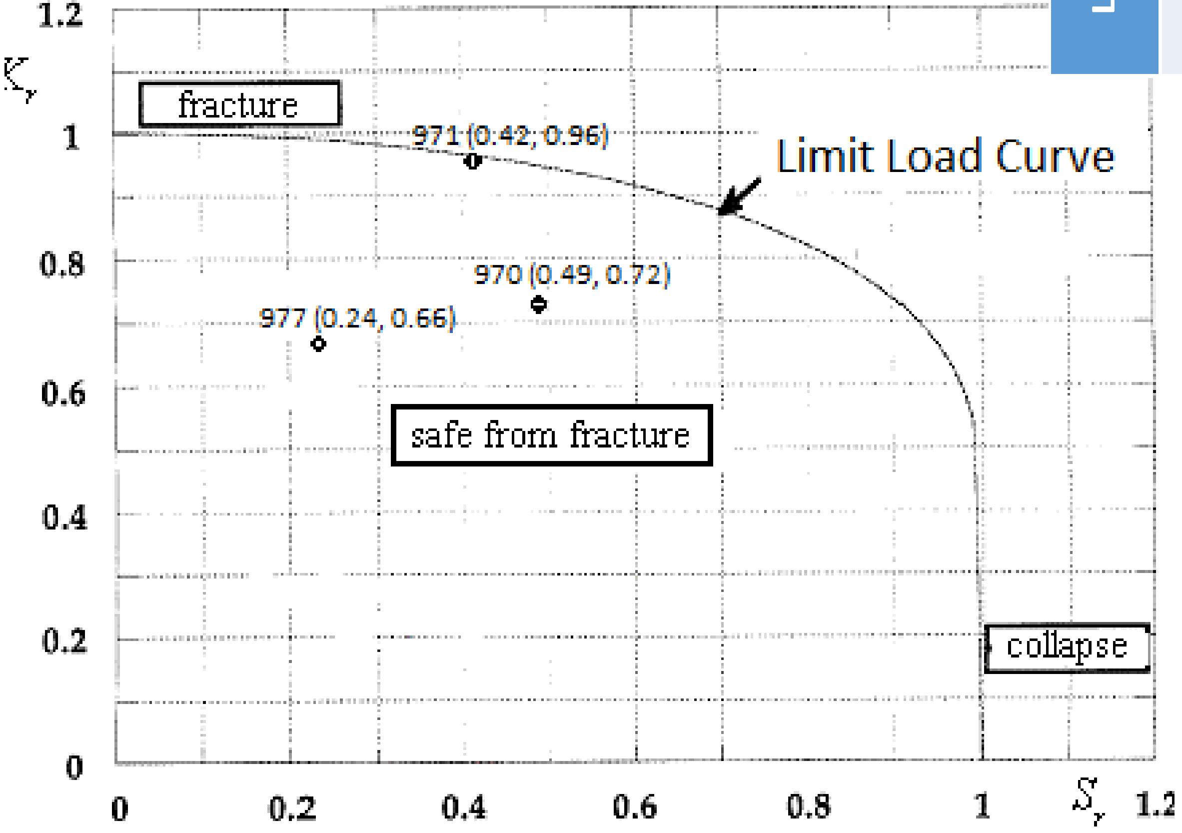
$$\frac{K_{eff}}{K_{\mathrm{I}}} = \frac{\sigma_c}{\sigma}\left[\frac{8}{\pi^2}\ln\sec\frac{\pi}{2}\frac{\sigma}{\sigma_c}\right]^{1/2}$$



where $K_{\mathrm{I}} = \sigma\sqrt{\pi a}$, is the stress intensity factor, K_{eff}, its effective value, was introduced instead of δ ($K_{eff}^2 = \delta\sigma_Y E$), and σ_Y, Yield Stress (YS), was replaced by plastic collapse stress σ_c, value in between YS and tensile strength (TS), taken as an adequate yield criterion for structures like pressure vessels. Finally, $S_r = \sigma/\sigma_c$ and $K_r = K_{\mathrm{I}}/K_{\mathrm{Ic}}$ are defined, as convenient non-dimensional parameters

FAD and Risk matrix

Risk		Consequence category				
		VL	L	M	H	VH
Likelihood category	VH					971 defect 1.1
	H					977 defect 2.5 970 defect 5.6
	M					
	L					971 "new" defect*
	VL					



In all 3 cases, actions were needed, taking into account specific conditions, as follows:

- Defect 2.5: it was decided to remove it by grinding and then to repair PV 977 by welding, [19].
- Defect 5.6: repair welding was not an option, so a special design solution in the form of a stiffener was applied for PV970
- Defect 1.1: since neither repair welding nor the special design solution was an option, and additional NDT from the inner side of the vessel (VT, MT) did not reveal the presence of this defect, it was decided to use more advanced UT for additional testing.

PRESSURE VESSEL 971 - INSPECTION IN 2022

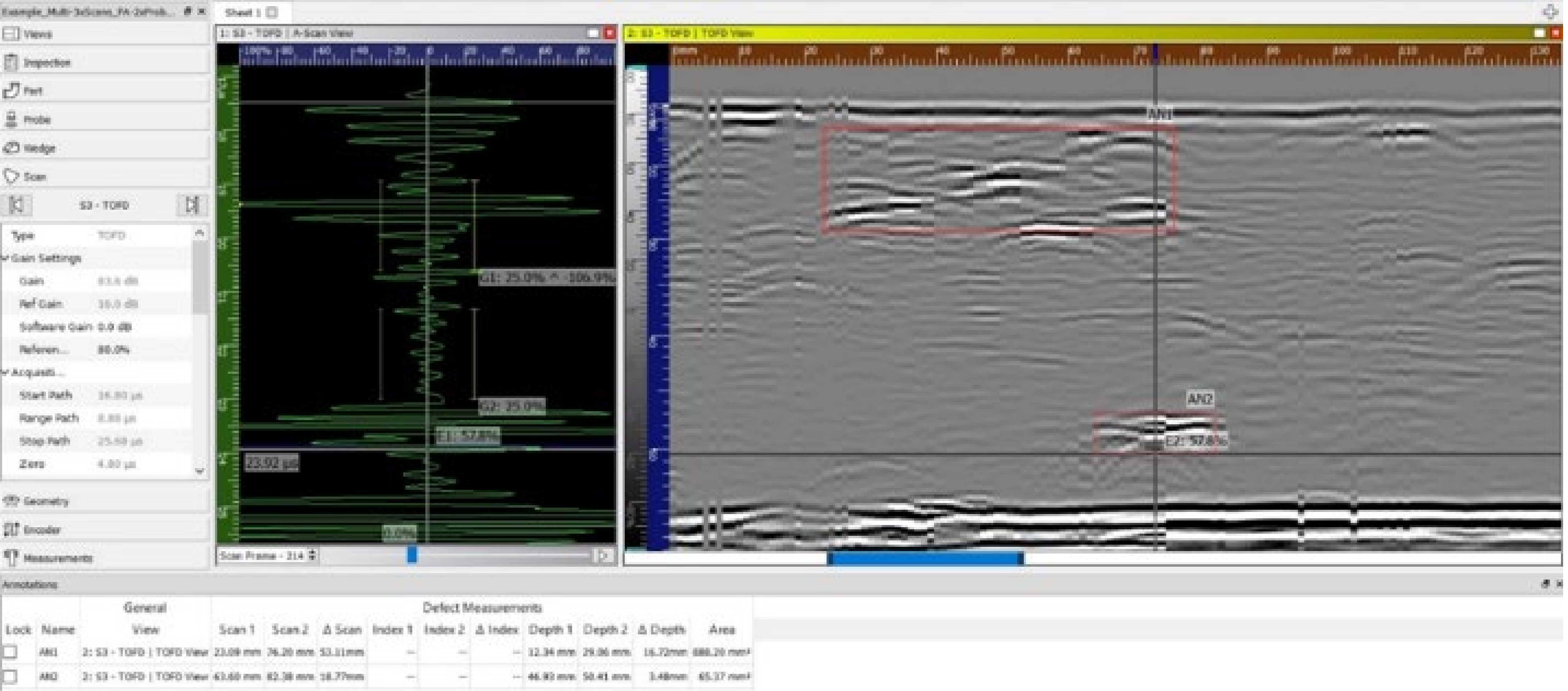
Having in mind this analysis, advanced UT techniques, PAUT and TOFD, were recently applied as the optimal combination to define in more precise way dimensions and location of defect 1.1. Testing was performed using the Sonatest Veo+ 32/128 device with Sonatest UT Studio + software. Transversal waves were used, sound velocity of 3240 m/s, impulse-echo method, along with Sector scanning and test amplification 45,5 dB. Contrary to the conventional UT, two indications were found instead on a single one:

- The first one with length 53.1 mm, and depth 16.7 mm (from 12.4 to 29.1 mm);
- The second one with length 18.8 mm, and depth 3.5 mm, from 46.9 to 50.4 mm).

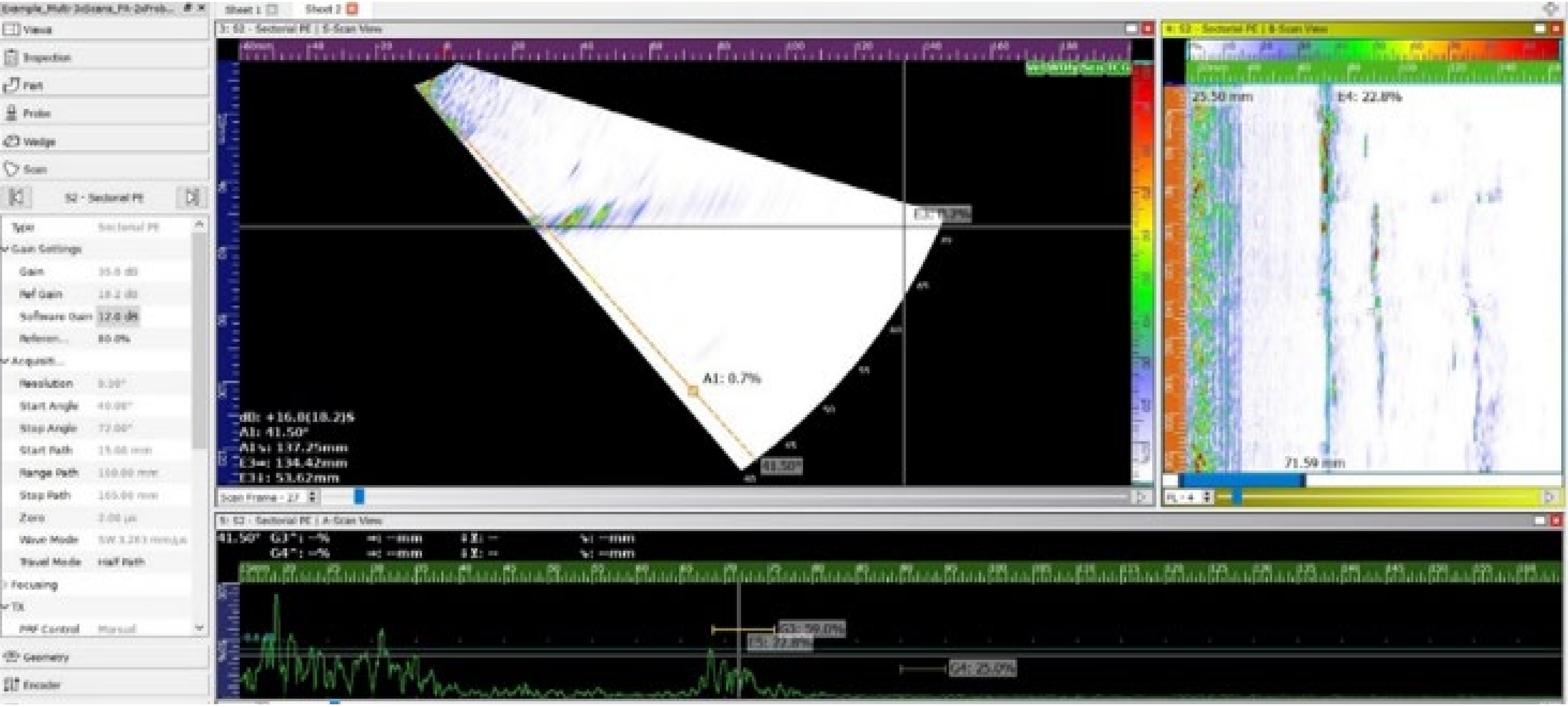
All necessary details of the UT testing by combination of PAUT and TOFD advanced techniques are presented in Fig. 4, where the first defect is denoted by AN1, and the second one by AN2.

TOFD

		General	Defect Measurements								
Lock	Name	View	Scan 1	Scan 2	Δ Scan	Index 1	Index 2	Δ Index	Depth 1	Depth 2	Δ Depth	Area
☐	AN1	2: S3 - TOFD | TOFD View	23.09 mm	76.20 mm	53.11mm	--	--	--	12.34 mm	29.06 mm	16.72mm	888.20 mm²
☐	AN2	2: S3 - TOFD | TOFD View	63.60 mm	82.38 mm	18.77mm	--	--	--	46.93 mm	50.41 mm	3.48mm	65.37 mm²



PAUT


Sheet 1
Sheet 2
Views
Inspection
Part
Probe
Wedge
Scan
Type
Gain Settings
Gain
Ref Gain
Software Gain
Resolution
Start Angle
Stop Angle
Start Path
Range Path
Stop Path
Zero
Wave Mode
Travel Mode
Half Path
Focusing
Geometry
Encoder
A1: 0.7%
25.50 mm
71.59 mm

For the internal crack with 2c=53.1 mm and 2a=16.7 mm:

- $K_I = Y(a/t, a/c)(pR/2t)\sqrt{\pi a} = 1{,}01(87)\sqrt{8.35\pi} = 450\ MPa\sqrt{mm}$, $K_R = K_I/K_{Ic} = 0.28$.

Ratio between net cross-section stress and collapse stress in now:

- $S_R = \sigma_n/\sigma_F = 87 \cdot 1.5/575 = 130.5/575 = 0.23$

Point coordinated in the Fracture Assessment Diagram (FAD) are (0,23; 0.28), the level of fracture likelihood is 0.3, and the risk level medium, not very high.

Risk		Consequence category				
		VL	L	M	H	VH
Likelihood category	VH					971 defect 1.1
	H					977 defect 2.5 970 defect 5.6
	M					
	L					971 “new” defect*
	VL					

Conclusions

- The results of that research were officially accepted, so that the scope of repair was dramatically reduced, due to which unnecessary costs were avoided as well as risks of occurrence of new defects caused by repair welding.
- Fracture mechanics has brought significant changes in engineering practice. The fracture mechanics criteria were adopted instead of traditional standards on acceptable defects.
- Fracture mechanics has become an important tool in the hands of engineers whose job is to prevent fracture from on one hand, and to not point unnecesarry repair on the other hand.
- Advanced NDT methods are crucial technique for more precise defect detenction and consequent structural integrity assessment and risk analysis

Thank you

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- As ESIS president, do you have some regional targets?
- How do you think to achieve these targets?
- What kind of antecedents can be taken into consideration in emphasizing „regional role”?
- What kind of domestic events help in extension of knowledge basis of the experts and which professional organizations can contribute to this?
- Is it possible to provide a short insight on your journal DIVK to the Hungarian community (establishment, editorial board, profile…)?
- We know that you were involved into governmental activity. In which area, how long, what goals and what results?
- What role did your father play in your career choice: inspirative or even opposite? (*please bring a picture from the grave of your father*)
- Looking at the NDE 4.0 could we define an area in which our countries could collaborate and present joint results in TC-17 in international event in Belgrade or in Budapest?