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Local Displacements Concept and its Applications to Fatigue Analysis of Non-Machined Weldments

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ABSTRACT: *Computerized approach to fatigue analysis of weldments on the basis of local displacements concept is presented. In accordance with this concept, displacements, corresponding to representative volume of metal with R_0 radius, are analysed. Concept applications to non-machined fillet welds are given: design of joints with fatigue curve development and fatigue limits calculations, in-service assessments of nozzle-to-tank weldments.*

Introduction

Fatigue strength analysis of welded structures includes determination of local stress-strain fields near concentrators with near-zero radii; interpretation of these multi-axial fields in terms of fracture mechanics; applications to real weldments with shape imperfections and random variations in weld geometry (1).

Fundamental question of weldment fatigue strength analysis is stress concentration definition. Measurements of concentrator tip radii along non-machined fillet welds show that the ones for weld root and weld toe have as a rule near-zero random variation. Therefore, effective values of stress concentration factors are calculated to provide correlation with fatigue tests data. These effective values depend on weld joint geometry and loading scheme. Fatigue design curves are separated into different classes of weldments, but this separation sometimes has no detailed methodical ground.

Local displacements concept

Consistent approach to fatigue analysis is as follows: to introduce concentration factor value and describe processes of damaging, fatigue crack initiation and growth for some finite volume of metal. This approach, named local displacements concept, had been proposed by V.Vinokurov and V.Aladinsky (2) specially for complex fatigue strength analysis of weldments.

This concept is based on the consideration of small representative volume of metal in the form of a sphere (for 3-D problems) and a circle (for 2-D ones) with the centre in the concentrator tip. It is supposed that the local strain-stress fields and corresponding damage processes inside the metal volume are completely defined by local displacements: displacements of material points of the volume surface.

Some principal features of local displacements concept can be mentioned.

1. The key moment of the concept is selection of the representative radius R_0. Rough estimations show that this radius is of the order of 10^{-3} m. This metal volume is treated as homogeneous solid media which accumulates damage and controls the inner fracture processes. The radius R_0 reflects metal sensitivity to stress concentration, and the «best fit» value of R_0 provides adequate fatigue estimations for full-scale concentration diapason: from smooth cylindrical specimen to crack tip. The ratio of R_0 to joint characteristic dimension is a measure of size effect in fatigue. Analysis of non-machined fillet welds and cracked specimens fatigue data shows that the radius for low-carbon and low-alloyed steel weldments is defined by the range of 0.32...0.6 mm.

2. Damage accumulation equations as well as failure criteria are formulated in terms of local displacements. The concept provides potentialities for adaptation and development of analysis: depending on the problem under consideration, selected components of local displacements or set of local displacements functions are used. Elastic description, using

radial component of local displacements, provides adequate fatigue analysis of non-machined weldments and covers fatigue strength problems of V-like concentrators and planar discontinuities by the same systematic description.

3. The local displacements are determined by numerical methods. The authors developed computer realization of the concept on the basis of finite element method. As applied to welded structure, the computer analysis connects the local displacements and nominal loads, and the effects of joint geometry and loading scheme are considered by explicit order. Unified finite element mesh is used for representative volume discretisation, procedures of modelling data treatment and analysis are built into the post-processor. Therefore, software becomes the integral part of strength assessment method.

Local displacements analysis of non-machined fillet welds

The stages of local displacements concept analysis are presented below in application to fatigue of non-machined fillet welds. As mentioned above, the analysis uses radial components of local displacements which are modelled by elastic finite element method.

Design of lap joints leads to the stress concentration located in the zones of weld to base metal transition (Fig.1): weld root (crack-like concentrator, point A) and weld toe (V-like one, point B).

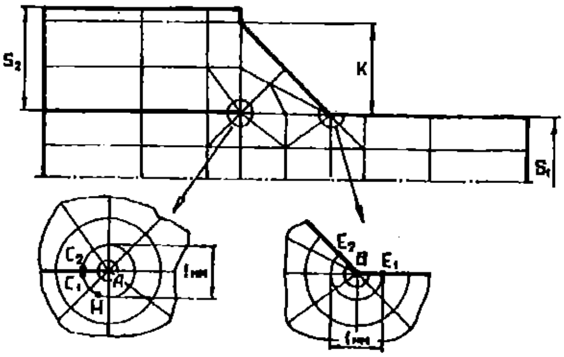
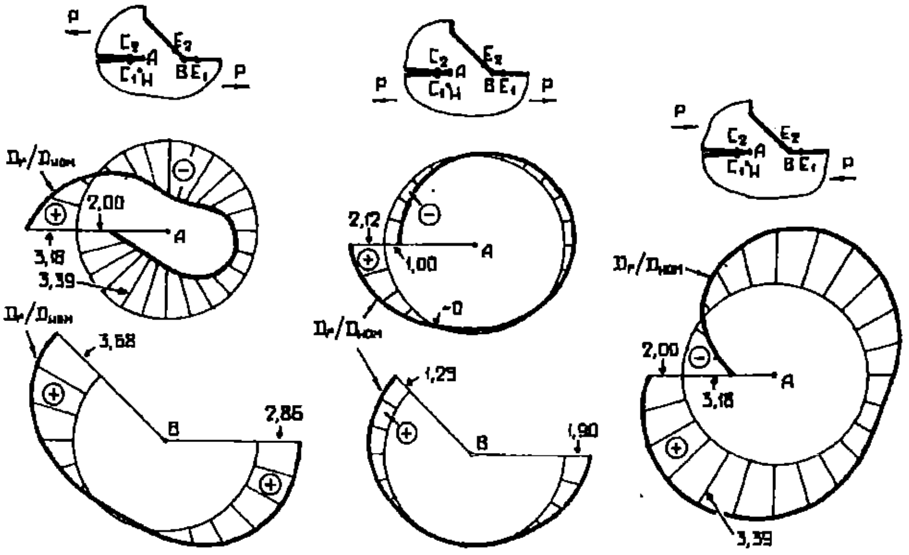


Fig.1. General details of fillet welded joint.

Using finite element method the radial local displacement (D_R) distributions around these concentrators with zero radii are analysed in order to obtain the maxima of D_R values. These maximum tensile values of D_R, named as $D_{R\max}$, define zone of fatigue crack initiation and growth direction (perpendicular to the $D_{R\max}$ radius).

For load-carrying fillet welds under tensile loading $D_{R\max}$ locations correspond the radii orientations AC_2 or BE_2 (Fig.2, a). Depending on the joint dimensions two fatigue failure modes are possible: from the weld root or weld toe. As applied to non-load-carrying welds the highest $D_{R\max}$ location corresponds the AC_1 radius (Fig.2, b), and the fatigue crack grows from the weld root across the main plate. The analysis of load-carrying welds under compression shows that the highest $D_{R\max}$ acts in the main plate in the through-thickness AH direction (Fig.2, c), and the failure propagates along the fusion line.



a) b) c)

Fig.2. Loading scheme and angle variation of non-dimensional local displacements.

In accordance with local displacements concept the local stress (σ_D) is defined:

$$\sigma_D = E\,D_{R\max}/R_0 \tag{1}$$

where R_0 – representative radius, E – elastic modulus.

Local stress concentration factor value (α_D) is introduced by the conventional way:

$$\alpha_D = \sigma_D / \sigma_n \qquad (2)$$

where σ_n – nominal stress.

The α_D values become independent of the concentrator radius, if the one tends to zero. And as applied to non-machined fillet welds these limiting (effective) values are determined in the analysis. Stress concentration is governed by loading scheme and joint elements dimensions (main plate thickness S_1, attachment thickness S_2, leg length K).

Fig.3 shows the effect of dimension factors on the α_D values for load-carrying fillet welds. The maximum α_D values (thick lines) define the local tension level, place of crack initiation, crack growth direction. If the main plate thickness is small, the α_{DA} values are greater than the α_{DB} ones, and fatigue failure of main plate metal starting from the weld toe is possible. As the main plate thickness increases the α_{DB} values become greater than the α_{DA} ones. In accordance with this result, the fatigue crack initiates at the weld root and grows across the attachment or weld leg.

As can be seen, the local stress concentration increases if the main plate thickness S_1 increases, and decreases with the weld leg length K (K/S_1 ratio) increasing.

Local stress concentration factors and local stress values can be determined for arbitrary loading scheme and joint geometry. These data are used for fatigue life assessments as well as for design curves elaboration.

In this part local stress analysis of fatigue tests data is presented. The analysis is based on the conventional data in terms of nominal stresses, stress ratio and number of cycles which include 485 points from different sources for transversal and longitudinal fillet welds (low-carbon and low-alloyed steels weldments with ultimate strength of base metal up to 800 MPa). These data have been recalculated in terms of elastic local stresses: the nominal stress values were multiplied by the α_D values for corresponding weldment dimensions and loading scheme and brought to local stresses range $\Delta\sigma_D(N, R)$ as a function of number of cycles N and stress ratio R.

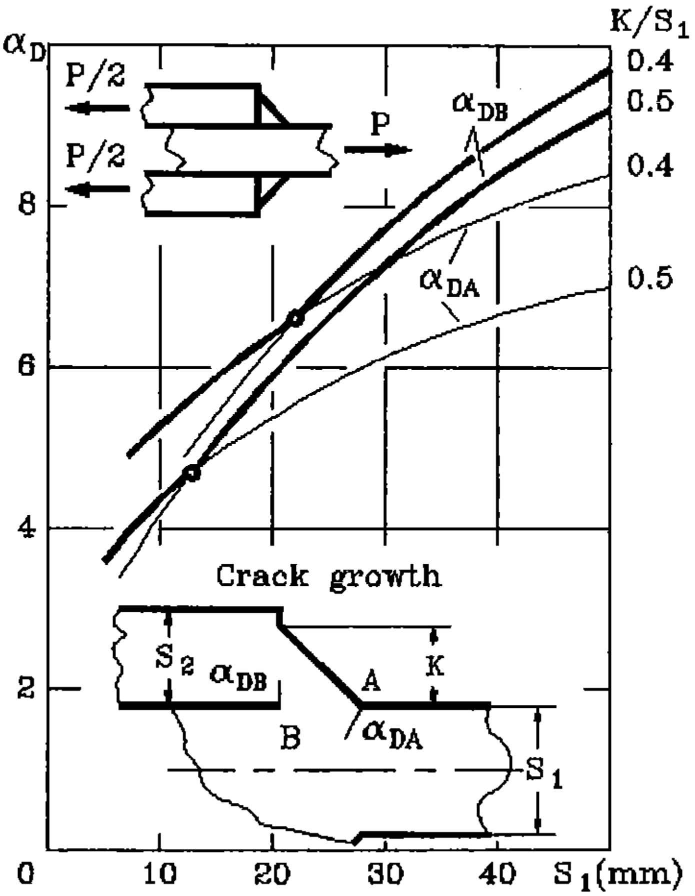


Fig.3. Local stress concentration factor as a function of S_1 and K/S_1 ratio ($S_2/S_1 = 0.5$).

Applications to fatigue analysis of non-machined fillet welds

Statistical treatment, executed separately for transversal and longitudinal welds, shows that after reducing to symmetric cycle ($R = -1$) $\Delta\sigma_D$ functions are as follows:

$$\Delta\sigma_D(N,-1) = \Delta\sigma_D(\infty,-1)\left[(N_T/N)^q + 1\right] \tag{3}$$

for transversal fillet welds, and

$$\Delta\sigma_D(N,-1)=\Delta\sigma_D(\infty,-1)\left[(N_L/N)^q+1\right] \tag{4}$$

for longitudinal ones, where $\Delta\sigma_D(\infty, -1) = 252$ MPa – local fatigue limit value for non-machined weldments, $q = 0.422$, $N_T = 6.65\times10^5$ and $N_L = 1.214\times10^7$ cycles. The difference between N_T and N_L values is conditioned by the differences in high-tensioned volumes of metal.

The equations (3) and (4) are expressed in the unified form, if the non-dimensional number of cycles $\tilde{N}\left(\tilde{N}=N/N_T; \tilde{N}=N/N_L\right)$ is introduced. Consolidated fatigue tests data in terms of $\Delta\sigma_D$ and $\tilde{N}$ are presented at Fig.4. The data were consolidated in accordance with «all in the one heap» principle: non-load-carrying and load-carrying welds, stress ratio ranging from −1 to 0.6, main plate thickness ranging from 6 to 40 mm, the endurance was defined by fatigue crack length of order 1...5 mm as well as by weldment failure.

At Fig.4 the 50% confidence design curve is presented by the equation

$$\Delta\sigma_D(\tilde{N},-1)=252\left(\tilde{N}^{-0.422}+1\right). \tag{5}$$

On the basis of this curve the stress safety factors of 1.65 and 1.81, corresponding to 95% and 99% probability of survival are introduced.

The resulting scatter of consolidated fatigue data is conditioned by probabilistic effect of a number of factors: metal properties, concentrator radii, residual stresses, weld imperfections. As can be seen, some points are located higher than the upper boundary of 95% confidence region. The most part of these points correspond the weldments with weld toe peening and the rest of the ones to tests up to failure of weldment.

Local displacements reflect the stress concentration level irrespective of its source (V-like cut or crack). Therefore, the local fatigue limit value for non-machined weldments is in close relation with the corresponding threshold value of stress intensity factor K_{th} (3). Based on the data presented, local fatigue limit value under pulsating loading (stress ratio R is equal to 0), $\Delta\sigma_D(\infty, 0) = 220$ MPa, was obtained. This value defines calculated threshold for weldments: $K_{th0} = 7\,\mathrm{MPa}\sqrt{\mathrm{m}}$.

As can be seen, the local stress design curves and local stress concentration factor values provide the basis for fatigue assessments of weldments.

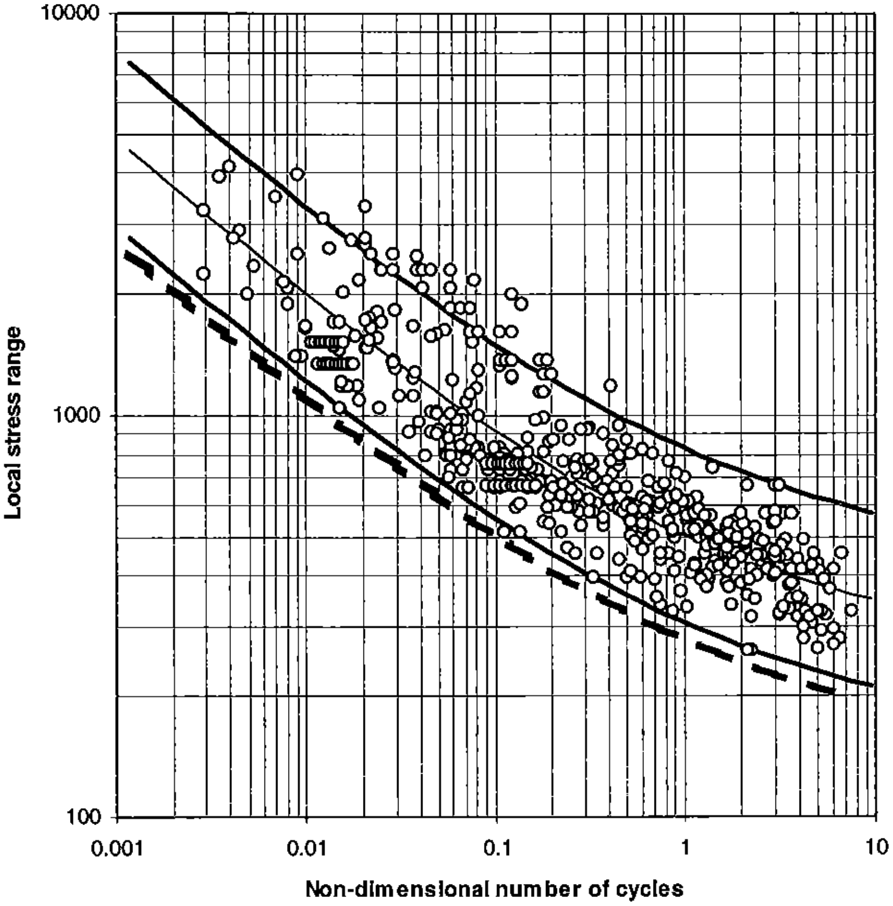


Fig.4. Consolidated test data (points) on fillet welds fatigue in terms of local stresses range (symmetric cycle) and non-dimensional number of cycles. Solid lines show the 50% confidence curve and 95% confidence region. The broken line corresponds to the 99% probability of survival.

The results show that the local stress concentration factor, depending on joint geometry and loading scheme, strongly governs the service life of the non-machined weld joints. On the one hand, as applied to fatigue cracks the local displacements analysis can be re-formulated in terms of stress intensity factors. On the other hand, local stress concentration factor value, calculated for non-cracked weldment, can be re-calculated to «initial» value of stress intensity factor. During fatigue crack growth the stress intensity factor increases from this «initial» value. As a result of such continuous analysis, local stress concentration factor can be considered as the important stress-strain parameter governing the stages of fatigue crack initiation and controlled growth.

Fatigue analysis and service assessments of nozzle-to-tank weldments

The local displacement concept has been applied for analysis of several failures of nozzle-to-tank weldments in which fatigue surface cracks have been detected.

Stages of crack initiation and growth up to failure were analysed by 2-D axisymmetric (output nozzle) and complete 3-D (input nozzle) finite element modelling.

Firstly, radial local displacements distributions were analysed. It was shown that high level of local stress concentration is the reason of fatigue crack initiation. For service pressure of 7.5 MPa, the maximum value $\alpha_D = 11$ with corresponding stress intensity factor of $56\,\mathrm{MPa}\sqrt{\mathrm{m}}$ were calculated. In accordance with local displacements distribution the crack initiation angle was determined.

Then, damage accumulation models, developed on the basis of local displacements concept in terms of stress intensity factor (4), were used to estimate number of cycles before crack initiation as well as fatigue crack growth rate. The weldments were loaded in accordance with service data on pressure pulsation and shut-down events. Fatigue crack growth was modelled by finite element mesh re-configuration. The modelling was executed up to failure, governed by fracture toughness value of $100\,\mathrm{MPa}\sqrt{\mathrm{m}}$. The modelled fatigue cracks trajectories correspond well to the real crack paths detected (Fig.5).

Fig.6 presents the variations of maximum value of stress intensity factor and crack dimensions due to fatigue for input nozzle.

On the basis of the analysis the residual life curves have been proposed, relating the crack size (height or length) detected during the last examination with the time before failure (Fig.7).

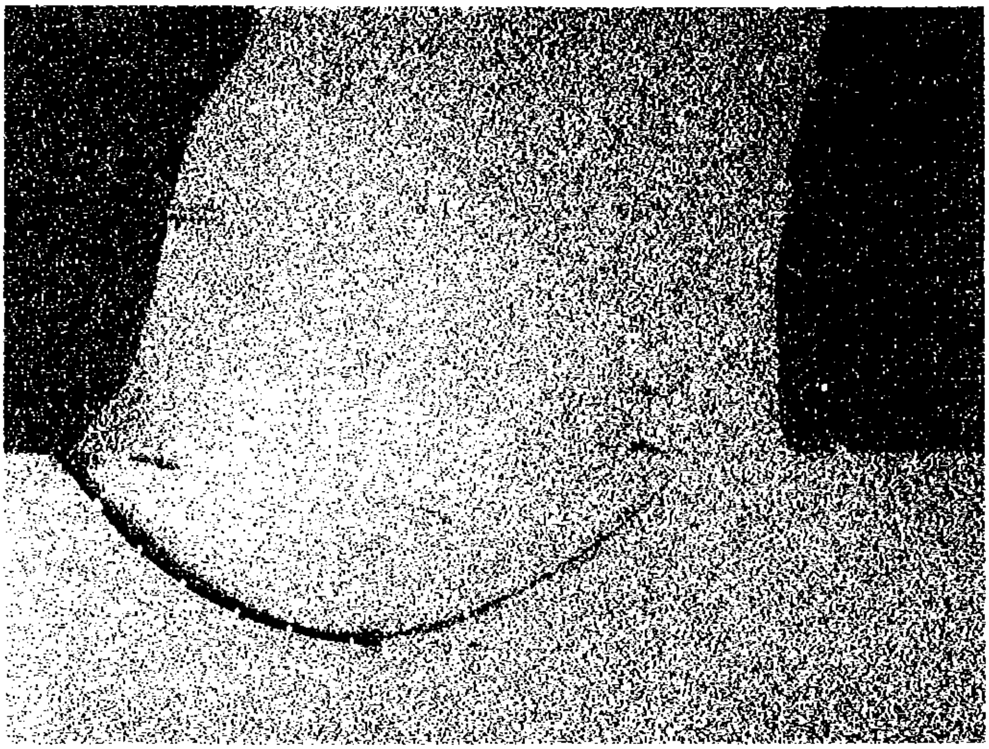
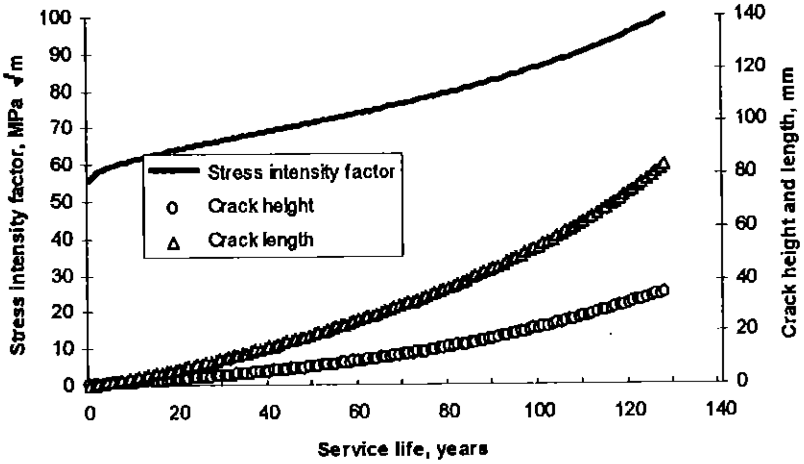


Fig.5. Detected and modelled (broken line) fatigue crack paths in nozzle-to-tank weldment.

Conclusion

The local displacements concept provides well grounded fatigue analysis of non-machined fillet welds. In accordance with this concept the local stresses and its concentration factor are introduced which strongly govern the stages of crack initiation and growth. The concept can be used as the numerical basis for fatigue design curve development as well as for verification of the existing ones. The finite element realization of the concept is a method of computerized fatigue and fracture assessments of welded structures.



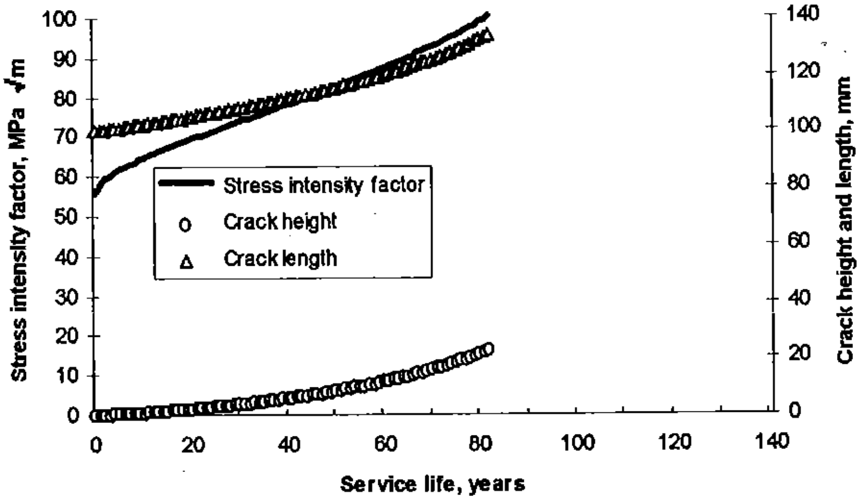


Fig.6. Examples of graphs relating stress intensity factor, surface crack height and length, tank service life for initially undamaged weldment (top) and weldment with 100 mm length brittle zone (bottom).

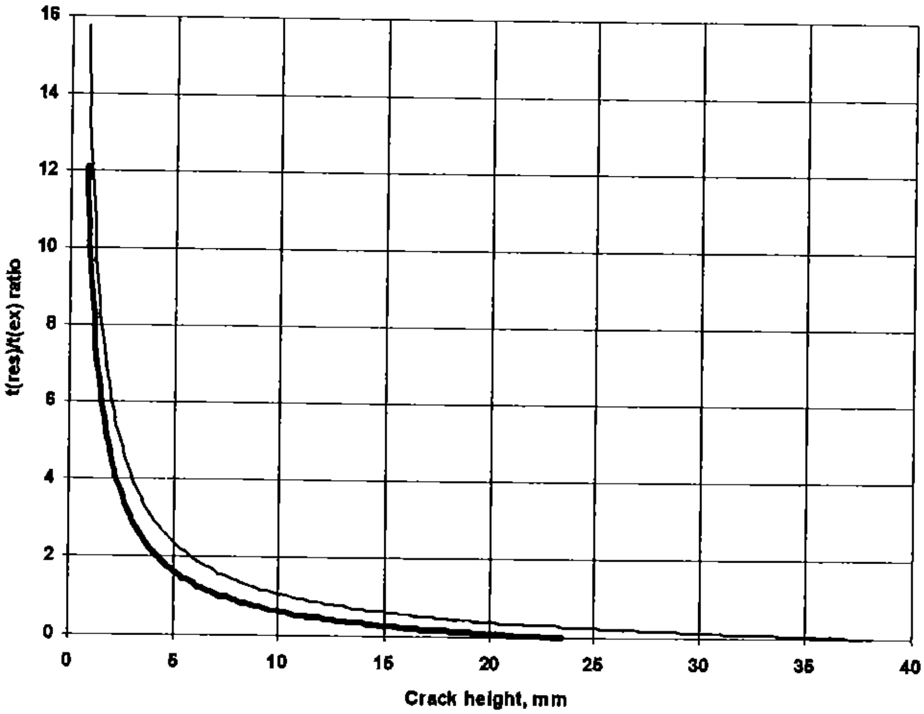


Fig.7. Examples of relations between crack height detected by the examination at time t(ex) and residual time before failure t(res) for probability of survival: 50% – thin line, 95% – thick line.

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