The New Purposes of Destroyment Mechanics of Dissimilar Bodies

A K Gumerov¹,a, B N Mastobayev¹,b, A R Valeev¹,c
¹Department of Oil and Gas Pipeline Transportation and Storage, Ufa State Petroleum Technological University (USPTU), FSBEI HE, 1 Kosmonavtov St., Ufa, 450062, Russia

E-mail: ⁴gumerov@list.ru, ⁵thng@mail.ru, ⁶anv-v@yandex.ru (corresponding author)

Abstract. Recently, with the rapid development of fracture mechanics, the range of tasks that it allows to solve is also expanding. The article provides a brief overview of problems with singular stress fields starting from a simple fissure and up to V-shaped elements made of dissimilar materials. It shows that the fissure is a special case of an entire class of problems. The destruction of pipelines, as well as all other structures, occurs through the birth and development of fissures. It means that it is more important to study problems with singular stress fields in the oil and gas industry. The article provides a solution to a general problem from which all known solutions follow in particular cases. But if in the case of a fissure the dimension of all stress intensity coefficients is the same and constant, then in general the dimensions of the KIN are determined by the values of a parameter that depends on the elastic properties of materials, as well as on the crack opening angle. This property of KIN, causes difficulties with calculating of strength. Therefore there is a problem - how to determine the strength conditions of structural elements with such singular points. This problem requires further research in this area.

1. Introduction
Pipeline destruction, like any other constructions, occurs through the initiation and growth of fissures. [1-5]. That’s why during the last century the rapid development of destruction mechanics was noticed. It studies characteristics of tense modes around fissures and suggests evaluation criteria of constructions located nearby the fissures. Fissures are differed from other (classic) defects in that that with any load in the vertex area fissures singular field (σ→∞) is; the closer to the vertex of the fissure the higher the tension. According to classic opinions, any constructive element must be crashed with any tense because at the vertex of fissure tense will go over the toughness limit of any material. Actually, we see other thing: constructions with fissures are working and some of them are working for a long time. It means that classic strength theory [6, 7] is unsuitable if there are fissures because of σ→∞-singularity. For cases like that mechanic of destruction offers special strength criteria: force (based on coefficients of tension intensity- CTI), power (based on energy balance), Deformation (using the opening of fissures) [8].

There are other methods that look like fissures, for example, non-wells (welding defects) [9, 10], metal separations (metal defects) [11, 10]. These defects are called fissure-looking (by their form) and those criteria that offers destruction mechanics is also used for them [13, 14].
With the expansion of the range of construction materials, particularly with integrating of layered and composite materials it was found that fissures behave themselves differently depending on their position. [12]. As the subjects of a separate study appeared “interphase fissures”, located on the border of 2 materials (non-welds in compounds of dissimilar materials, separation in bimetals and multilayer composite materials) [15]. Features of interfacial fissures and their destruction criteria aren’t known yet.

Then the interest was concentrated on fissures crossing the border between 2 different materials (bimetals and composite materials). It was found that fissures cross borders between different materials easy on one way and on other way they do it much harder. Particularly on this feature high strength of composite materials was found. Borders of phases block fissure developments there. Features of such “cross fissures” and destroying criteria for them are also not fully discovered and require clarifying. One of them is that sizes of CTI aren’t the same as sizes of the viscosity of $K_{IC}$ - destroying for materials.

Then other singularity principals appeared, particularly because of wide application welding technologies. It is V-shaped form elements, that are located in welding connections, particularly, transformations from the angle weld to the main metal [15, 13]. With the wide using of different repairing technologies [16, 17] the problem of evaluation of such singularities [5] on strength and remaining lifetime been actualized [18]. Cyclic loads and temperatures can accelerate the formation and growth of fissures, it is more markedly in singularity zones. If in these zones isolation coverage is damaged and at the same time the electrochemical protection works then there all conditions for the occurrence of local stress corrosion

With expanding the range of materials, particularly using composites, singular elements inside materials have appeared. Some features of these elements are discovered [19], but it did not come to the practical use of results in the gas industry.

2. Methods
As we see, the range of varieties became much wider and the necessity to discover them from single position appeared to determine the limits of applicability of approaches to fracture mechanics and determine general rules and solve the issues more efficiently.

Analysis of known types of stress concentrators has shown, that $\sigma \rightarrow \infty$ singularity appears when there is geometrical and (or) mechanical features. On (Fig. 1) there are some elements that create singular fields of tensions around the special point $O$. Each previous element is to a certain extent a special case of the subsequent one. For example, case a) comes from a case b), if the opening angle is directed to zero; case c) goes into d), if the features of materials 1 and 2 are known as the same; from the case e) we can go to the case f), if the material 2 is known as empty. (module of elasticity $E_2$ aims to zero), and materials 1 and 3 are known as the same. That’s why all cases in (Fig. 1) can be reviewed as the special cases of a more general case. Then the simple fissure in uniform material that is a subject of studying mechanics of destruction will be only the simplest particular case of the general task about singularities.

![Figure 1](image-url) A scheme of elements that develop a singular field of tensions around point $O$: 1, 2, 3 – materials, differed by their mechanical features; fissure in uniform material (a); dihedral angle in...
uniform material (b, c); interphase fissure (d); cross fissure (e); composite dihedral angle (f, g); boundary point of intersection (h); internal V-shaped elements in a heterogeneous materials (i, k).

As an example, let’s stop our attention on g), that is convenient in methodическом плане и has its own practical importance. So, let’s choose практичную экземпля, that is shown on pic.2 and set a task to learn particularities of tense modes in the area of any point O – vertex of compound dihedral angle.

Using a method of complex potentials [20]. Let's assume that the field of elastic displacements and deformations does not depend on one of the Cartesian coordinates, for example, on z. Moving on to the flat problem [8]. In this particular but important case all displacements and tensions can be submitted using analytic functions $F(z)$ and $\Psi(z)$ of complex variable $z = x + iy$ (the same meaning of Z for the Cartesian coordinate and complex variable doesn’t have to lead to confusion. These functions are called complex potentials. The equations that the complex potentials must satisfy have the form:

\[
\begin{align*}
\sigma_x + \sigma_n &= 2[F(z) + \overline{F(z)}]; \\
\sigma_n - \sigma_x + 2i\tau_n &= 2\ell^{2i\alpha}[\tau F'(z) + \Psi(z)]; \\
2\mu(u + iv) &= \chi \varphi(z) - z\varphi'(z) - \psi(z).
\end{align*}
\]

(1)

(2)

Here $u, v$ – are offsets of points along x and y-axes, $y$ that’s why; $\mu, v$ – shear modulus and Poisson's ratio of the material; $\chi = 3 - 4v$ (при $\varepsilon_z = 0$); $\varphi'(z) = F(z)$; $\psi'(z) = \Psi(z)$; $\sigma_1, \sigma_n$, $\tau_n$ – components of tensions’ tensor in the coordinate system (t-n); $\alpha$ – axel between axises x и t (reference direction from x to t). If $\alpha = \theta$, then tensions $\sigma_1, \sigma_n, \tau_n$ go to $\sigma_t, \sigma_0, \tau_0$.

![Figure 2](image)

Figure 2. Is a design scheme of the element with V-shaped border between materials (a) and accepted coordinate system (b).

The problem diagram shows that the set of desired solutions admits a similarity group: functions $F(z)$ и $\Psi(z)$ have to satisfy the equation $C_2 f'(C_1 z) = f(z)$, where $C_1$ и $C_2$ – some permanents. The physical meaning of this condition is that the general look of the tension field saves if we change (increase or decrease) the scale of area in the surrounding of singular point. For example, if the scale is changed in $C_1$ times (we look at the picture with the increasing= $C_1$), then we “will see” that tensions on all points are increased in $C_2$ times. However, the qualitative picture does not change. Conventionally, this feature is called the principle of the microscope. It follows from this feature that the complex potentials must have the power-law form:

\[
F(z) = A \cdot z^{-\lambda}; \quad \Psi(z) = B \cdot z^{-\lambda},
\]

(3)

where A, B, $\lambda$ – some permanents which could be valid or complex. The validity of this statement
can be verified by a direct method by substitution of expression (4) to equation (1). Using the functions (3) and the original formulas (1, 2), we obtain expressions for tensions:

\[
\begin{align*}
\sigma_0 &= K r^{-\lambda} \cdot f_0(\theta) ; \\
\sigma_r &= K r^{-\lambda} \cdot f_r(\theta) ; \\
\tau_{r\theta} &= K r^{-\lambda} \cdot f_{r\theta}(\theta).
\end{align*}
\]  

(4)

In expressions (4) a coefficient K is introduced which, by analogy with a fissure, should be called the coefficient of tension intensity - CTI. This coefficient is proportional to the tension. Functions \(f_0(\theta), f_r(\theta), f_{r\theta}(\theta)\) are describing the tension distribution. \(\sigma_0(\theta), \sigma_r(\theta), \tau_{r\theta}(\theta)\) in a circle \(r = 1\) at the tension respective to the value \(K = 1\). In addition to the polar angle \(\theta\), these functions contain the parameter \(\lambda\). So, the solution was divided on 3 multipliers that depend only on tension \((K)\), distance from a special point \((r^{-\lambda})\), and angular coordinate \(f(\theta)\).

One of the most parameters in solution of a task is \(\lambda\), that in this particular task can have 3 meanings; let’s call them \(\lambda_1, \lambda_2, \lambda_3\). Accordingly, substituting these values in expressions (4), we get several particular solutions. Then the general solution will be found as a summation of particular solutions (from the linearity property of the issue and the superposition principle):

\[
\begin{align*}
\sigma_0 &= K_1 r^{-\lambda_1} \cdot f_{01}(\theta) + K_2 r^{-\lambda_2} \cdot f_{02}(\theta) + K_3 r^{-\lambda_3} \cdot f_{03}(\theta) ; \\
\sigma_r &= K_1 r^{-\lambda_1} \cdot f_{r1}(\theta) + K_2 r^{-\lambda_2} \cdot f_{r2}(\theta) + K_3 r^{-\lambda_3} \cdot f_{r3}(\theta) ; \\
\tau_{r\theta} &= K_1 r^{-\lambda_1} \cdot f_{r\theta1}(\theta) + K_2 r^{-\lambda_2} \cdot f_{r\theta2}(\theta) + K_3 r^{-\lambda_3} \cdot f_{r\theta3}(\theta).
\end{align*}
\]  

(5)

Meanings of parameter \(\lambda\) depend on other elastic features of materials 1 и 2, that develop V-shaped element, and also on \(\omega\)-angle, developed by this element. As an example, there are shown dependence graphics \(\lambda(\omega)\) for the pair of materials that differing in modulus of elasticity by 5 times.

![Figure 3](image-url)

**Figure 3.** Meanings of parameter \(\lambda\) in depend on \(\omega\)-axel for a given ratio of elastic properties of materials, developing V-shaped element by the scheme (pic 2).

Exploration allowed to find a list of important features.

From the whole set of solutions only 2 meanings of parameter \(\lambda\) are positive and lead to \(\sigma \to \infty\) singularity if \(r \to 0\). Other meanings of \(\lambda\) – parameter are negative or zeros, that’s why in the area of singular point O their role is not important.

3. Results

The resulting solution under the appropriate conditions \((E_2 \to 0; \; \omega \to 0)\) goes to a known
solution for the fissure on the homogeneous material.

If there is a fissure then the sizes of all tension intensive coefficients are the same and permanent and are determined by the ratio

$$\sigma \sim K_1 / \sqrt{r} \quad \text{or} \quad [K] = \frac{P_{\text{a}} \cdot M}{H_{M^{1.5}}} = H_{M^{1.5}}. \quad (6)$$

In general situation is shown on (Fig. 2), sizes of CTI depend on $\lambda$-parameter and look like:

$$\sigma \sim K_r^{-\lambda} \quad \text{or} \quad [K] = \frac{P_{\text{a}} \cdot M}{H_{M^{\lambda}}} = H_{M^{\lambda-2}}. \quad (7)$$

Parameter $\lambda$ in this task depends on elastic features of materials $E_1 \neq E_2$ and on the $\omega$-angle then it turns out that the CTI, in this case, does not have a constant dimension. Moreover, CTI solutions (5) differ from each other in individual terms (particular solutions).

This feature of CTI occurs serious in difficulties with strength calculations. Usually in calculations like this use such term as fracture toughness $K_{\text{IC}}$. Its physical meaning is that it is assumed that the failure occurs at the moment when the stress intensity coefficient $K_{I}$ reaches its limit value equal to the value of $K_{\text{IC}}$. In the tasks with c V-shaped element (pic. 2) it’s impossible to simply express the condition of destruction because values $K_{I}$, $K_{\text{IC}}$ are not comparable and have different dimensions. That’s why the problem appears – how to determine the strength conditions of structural elements with such singular points. This problem requires an energy approach.

4. Discussion
Fracture mechanics in the previous version found limited use in the oil and gas industry; mainly in the analysis of the stress state around fissures and fissure-looking defects - non-welds. The solutions obtained in this work can be used in the analysis of the stress state and strength of welded joints with sharp heterogeneous transitions from the seam to the base metal of the pipe. It is also possible to analyze and make practical decisions in the use of composites and dispersed materials.

5. Conclusions
A solution of a General problem is obtained, from which all known solutions in particular cases follow [7, 8, 21], starting with a simple fissures and up to V-shaped elements made of dissimilar materials It is shown that the crack is a special case of an entire class of problems. The obtained solutions have real physical embodiments; singular stress fields can be observed on photoelastic models and compared with the obtained solutions. Features of strength estimation and directions of further development of fracture mechanics are shown.

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