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WELDING JOINTS FAILURE ASSESSMENT – FRACTURE MECHANICS APPROACH

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Abstract: *Fracture mechanics is a quite new discipline which characterize the brittle fracture processes and developing practical assessing and checking methods, in order to conclude upon the imperfections of a material. The presence of the imperfections makes the difference in fracture mechanics comparing with strength of material field which starts from the prerequisite that the material has no flaws. The main characteristics of the fracture mechanics are: it is accepting the existence of the crack/defect, studies the appearance and the crack propagation speed and the remaining life in safe service state of the structural element. The present paper is proposing a description of the failure assessment for a welded joint using fracture mechanics principles. Description and detailing of concepts are done for the ease of understanding the assessing algorithm.*

Key words: *welded joints, steel structure, fracture mechanics.*

1. Introduction

The classic theory is based on fact that the presence of a crack in a structural element, leads to exceeding its load capacity.

The actual principle is "*Living with defects*" which means that the "defect" parameter exists and must be assessed.

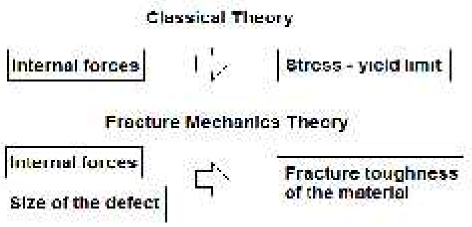

Fig. 1. *Classical theory versus fracture mechanics theory*

The main characteristics of the fracture mechanics are: it is accepting the existence of the crack/defect, studies the appearance and the crack propagation speed and the remaining life in safe service state of the structural element.

First studies on fracture mechanics were done by Alan Arnold GRIFFITH, a British aeronautical engineer which became "*father of the science of fracture*" [1]. He clarified quantitatively the breaking strength of cracked material and realized that weakening of the material due to a crack can be treated as a matter of equilibrium, in which the strain energy reduction of a body containing a crack that propagates, could be equalized by surface energy increasing due to area growth.

In 1955 arise concepts of "*fail safe*" and "*safe life*". The safe life design imposed that a structural component/element should be designed to last a predefined period of

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time. The *fail safe* design request that the failure of an element (designed component), must not jeopardise the safety of a structure, thus the structure can be safe for the people (e.g. occupants of a building). In practice the *fail safe* concept must contain a rigorous inspection plan in order to ensure that the cracks do not propagate to critical dimensions in the period of consecutive inspections. If a crack will propagate, the stress intensity in the other components of the structure, may increase; in this situation the result can be the total collapse of the structure, even if this component was designed to resist without the first damaged component.

George Irwin rediscovers the Griffith theories and he replaced the energy-balance approach with the study of the stress at the crack opening tip, thus introducing the stress intensity factor *K*.

This approach is adopted in fatigue design field in 1962 with the *Paris law* publishing. The law is linking the crack growth, resulted from the fatigue of the material in time of a stress cycle, to the stress intensity factor (SIF).

The theoretical development of fracture mechanics experienced new approaches in 60^{th}, when Wells is introducing the *critical crack tip opening* concept (1966) and the studies of Rice lead to introducing a new parameter named *J integral* (1968).

In 1970, year in which the American norm ASTM-E 399 [2] was published, are done the first tests in order to determine intensity factor at the crack tip K_{IC}, test done on specimens containing sharp defects crack type (fatigue pre cracked).

In past years was done a vast research in the fracture mechanics field, converging to developing new application in different engineering domains.

2. Stress at the Crack Tip

In 1957 George Irwin developed a theory based on fundamental fracture mechanics analysis of stress and strain state at crack tip [3]. This theory shows that the stress area from the tip of a crack is determined by the factor *K*. Analyzing the classic application and using Westergaard's theory of elasticity expressions, he characterized the elastic stress field in the proximity of a crack through the relations:

$$\sigma_x = \frac{\sigma_\infty \sqrt{\pi a}}{\sqrt{2\pi r}} \cos\frac{\theta}{2}\left(1 - \sin\frac{\theta}{2}\sin\frac{3\theta}{2}\right)$$
$$\sigma_y = \frac{\sigma_\infty \sqrt{\pi a}}{\sqrt{2\pi r}} \cos\frac{\theta}{2}\left(1 + \sin\frac{\theta}{2}\sin\frac{3\theta}{2}\right) \qquad (1)$$
$$\tau_{xy} = \frac{\sigma_\infty \sqrt{\pi a}}{\sqrt{2\pi r}} \cos\frac{\theta}{2}\left(\sin\frac{\theta}{2}\cos\frac{3\theta}{2}\right)$$

in which:

r, ¯ - polar coordinates in x-y plane and stresses as presented in figure 2.

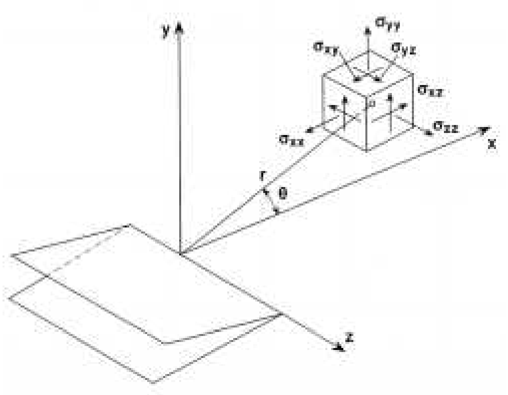


Fig. 2. *Stress field in the proximity of a crack*

Irwin, [3], had shown that there are three basic shapes of displacement of one crack surface relative to the other, and that they describe the behavior of cracks in all stress states. In Figure 3 are showed the basic shapes of displacement of elements which include the crack tip. Displacement shapes of a crack tip which lies in the x-z plane, can be described as follows:

- Mode I - crack propagation by cleaving, characterized by moving of crack surfaces in a way that they open symmetrically relative to the initial crack plane.

- Mode II - crack propagation by sliding, related to local deformation during which one surface slides along the other in the same plane, but in opposite directions.
- Mode III - crack propagation by shearing represents a case of local strain, during which surfaces slide along each other in the direction of the crack.

The most important is the crack opening mode I. The other modes and their combinations, the mixed mode loadings, are of minor significance. There is only a two-dimensional stress state at the surface of the plate, the so-called plane stress condition. Deeper inside a thick plate, a three dimensional stress state (*plane strain*) develops because of the restrained contraction in the thickness direction. Under this condition, the critical resistance of a material to fracture K_{Ic} is lowest. It is a material property called ***fracture toughness*** K_{mat}, which depends on the material, temperature and, to some extent, the rate of loading. In materials testing for fracture toughness, a minimum wall thickness of the specimens must be present in order to ensure the plane strain state.

The ***main check in fracture mechanics*** is given by the relation:

$$K_{apl} \leq K_{crit} = K_{Ic} \tag{2}$$

where K_{apl} is the stress intensity factor which depends on the applied stress intensity and on the dimensions and geometry of the crack and K_{crit} is the critical value of the stress intensity factor (toughness) which is a material characteristic (is determined by tests).

In other terms, the loading of a crack tip in terms of *SIF* must exceed the material resistance against fracture, i.e. fracture toughness. This is strictly true for brittle materials. In ductile materials, a plastic zone around the crack tip develops. If this plastic zone is small in comparison to the dimensions of the crack, the assessment can be done in the same way without a major error.

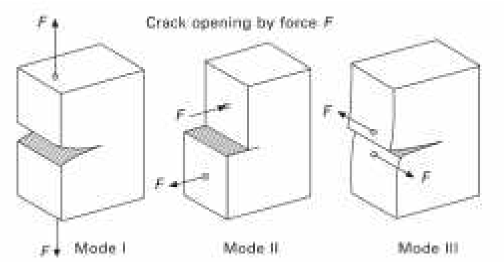


Fig. 3. *Different crack opening modes (mode I – Opening; mode II – In-Plane Shear; mode III – Out-of-Plane Shear)*

The basic the stress field equations for mode I (Figure 3) of crack opening, in polar coordinates (*r*, ¯), the stress field equations in the proximity of a crack becomes:

$$\begin{aligned} \sigma_x &= \frac{K_I}{\sqrt{2\pi r}} \cos\frac{\theta}{2}\left(1 - \sin\frac{\theta}{2}\sin\frac{3\theta}{2}\right) \\ \sigma_y &= \frac{K_I}{\sqrt{2\pi r}} \cos\frac{\theta}{2}\left(1 + \sin\frac{\theta}{2}\sin\frac{3\theta}{2}\right) \\ \tau_{xy} &= \frac{K_I}{\sqrt{2\pi r}} \cos\frac{\theta}{2}\left(\sin\frac{\theta}{2}\cos\frac{3\theta}{2}\right) \end{aligned} \tag{3}$$

2.1. Stress Intensity Factor Calculation for Different Cases

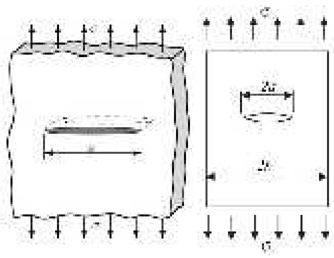
2.1.1. Plate with crack throughout the entire thickness – through thickness crack

In case of an infinite plate which is containing a crack flaw with length of *2a*, (Figure 4) and it's having a tension stress *σ*, the relation for the stress intensity factor will have the form:

$$K_I = \sigma\sqrt{\pi a} \tag{4}$$

The "*infinite plate*" denomination indicate that the crack/flow is very small comparing with the dimensions of the element (plate).

Analyzing the relation (4) can be noticed that the value of the K_I parameter is direct proportional with the stresses *σ*, which characterizes the global behavior of the plate.



a/b	Y
0,074	1,00
0,207	1,02
0,275	1,03
0,337	1,05
0,410	1,08
0,466	1,11
0,535	1,15
0,592	1,20

(a) (b) (c)

Fig. 4. *Plate with through thickness crack: (a)Infinite plate; (b) finite plate; (c) correction factor Y for finite plate*

If it is taken a finite plate of *2b* width (Figure 4 b), for the approximation of the stress intensity factor, it will be used the following relation:

$$K_I = \sigma\sqrt{\pi a}\left(\frac{2b}{\pi a}\tan\frac{\pi a}{2b}\right)^{1/2} \quad (4)$$

relation in which was used a correction factor $y = \left(\frac{2b}{\pi a}\tan\frac{\pi a}{2b}\right)^{1/2}$.

2.1.2. Plate with crack at a side – single edge crack

In case of an infinite plate under tension stresses which is containing a single edge crack with length of *a* and it's having a tension stress *σ*, the relation for the stress intensity factor will have the form:

$$K_I = 1.12 \cdot \pm \sqrt{®a} \quad (5)$$

In case of single edge crack, the *K* value increases with 12% - the edge crack tends to open different from the interior crack (Figure 5).

In case of finite width plate with single edge crack, is needed to introduce in the relation of stress intensity factor a correction factor in order to consider the bending moment effort which appear due to the non-symmetric flaw. In this case the relation becomes:

$$K_I = 1.12 \cdot \pm \sqrt{®a} \cdot k\left(\frac{a}{b}\right) \quad (6)$$

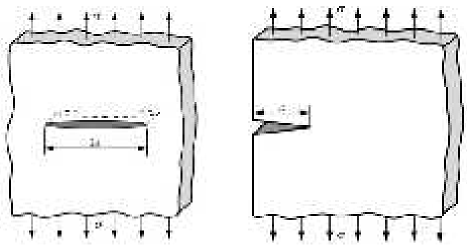
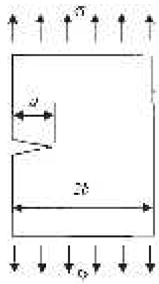


Fig. 5. *(a) Plate with through thickness crack; (b) Plate with single edge crack*

The value of the correction factor $k\left(\frac{a}{b}\right) = Y$ is presented in Figure 6.



a/b	Y
0.000	1.00
0.100	1.03
0.200	1.07
0.300	1.15
0.400	1.22
0.500	1.35
0.600	1.50
0.700	1.69
0.800	1.91
0.900	2.20
1.000	2.55

Fig. 6. *Plate with single edge crack – correction factors Y*

3. Determining the Crack Acceptability Based on Fracture Toughness

Elaboration of a methodology for determining the acceptability of detected cracks in a structure, has a major practical importance in the overall assessment and life integrity of a structure. The relation given by fracture mechanics links a parameter which describes the *stress intensity at a crack tip* to a material characteristic – *fracture toughness*. This relation provides the possibility of assessing the fracture conditions of the structural elements with defects (cracks).

This type of assessing can be done if the following elements are known:
- *material fracture toughness*
- *geometry and size of the crack*
- *resulted stresses from the applied forces*

The fracture mechanics based methodologies are permitting the following types of assessments:
- *Maximal crack dimension assessment* to which the structural element will not fail, named also the admissible crack dimension; for this type of assessing is needed the maximal stresses values and the value of the material fracture toughness;
- *Maximal stress value assessment* to which the structural element with a crack will not fail
- *Minimal fracture toughness value assessment* to the structural element with a crack; this assessment needs knowing the maximal stress value and the admissible crack dimensions.

Following the assessment procedures, can be determined a life time assessment of the structure. The methodology implies two phases:
- First phase in which it is determined the acceptability of the detected cracks in the structure (material and/or in welding seams)
- Second phase – fatigue assessment of the analysed structural elements based on loading events history.

Considering a simple case – a steel plate under tension (Figure 7), can be underlined the following types of fracture: *Brittle fracture* – controlled by the value of the applied tension force, dimension of the crack, material fracture toughness and geometry of the element; *Plastic fracture* – the net section in which the yielding phenomena appears, controlled by the applied tension force value, the yielding limit and the element geometry; *Rupture as a result of extended material yielding,* controlled by the applied tension force, crack size, material fracture toughness and the element geometry.

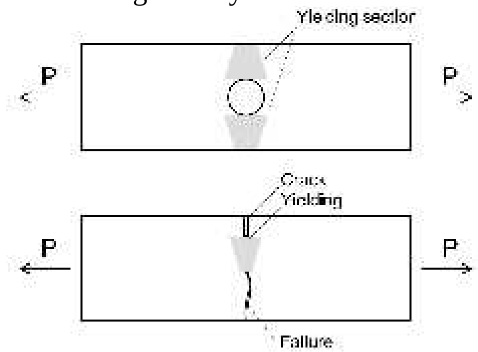


Fig. 7. *Describing fracture – plate under tension*

The transition domain between these types of fracture is governed by the interaction between the *brittle fracture* and the *plastic failure*. This is expressed through a dependency relation of two parameters K_r and S_r. These parameters are defined based on the geometrical dimensions of the structural element, crack dimensions and geometry, stresses that appear in the cross section following the applied loads, taken into account the fracture toughness of the material K_{mat}. The ***Failure Assessment Diagram*** (FAD) describes the interaction between the brittle fracture and plastic failure through a $F_f = f(S_r)$ function.

Structures using reasonably tough materials (high K_{Ic}) and having only small cracks (low K) will lie in the strength-of-materials regime. Conversely, if the material is brittle (low K_{Ic}) and strong (high yield strength), the presence of even a small crack is likely to trigger fracture.

Thus, the fracture mechanics assessment is a crucial one. The special circumstances that would be called into play in the upper right corner of Figure 8 in this regime, a cracked structure would experience large-scale plastic deformation prior to crack extension.

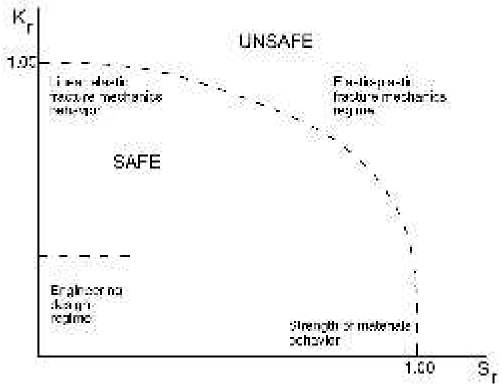


Fig. 8. *General plot of the ratios of the toughness and stress showing the relationship between linear elastic fracture mechanics and strength of materials as it relates to fracture and structural integrity [4]*

Damage tolerance is the philosophy used for maintaining the safety of structures. The use of fracture mechanics and damage tolerance has evolved into the design program for structures that are damage tolerant, designed to operate with manufacturing and in-service-induced defects.

Damage tolerance evaluation has been interpreted in the past as a means to allow continued safe operation in the presence of known cracking. This interpretation was incorrect. The damage tolerance evaluation can be detailed as a procedure of providing an inspection program for a structure that is not expected to crack under normal circumstances but may crack in service due to inadvertent circumstances. If cracks are found in structure elements, they must be repaired. The only allowable exception is through an engineering evaluation, which must show that the strength of the structure will never be degraded below ultimate strength operations or in-service conditions.

FAD represents an assessing instrument of the acceptability of a detected crack in the structural elements. The procedure is simple and consist in determining the K_r and S_r parameters for the particular case of the analyzed crack, then positioning of the points (K_r,S_r) in a diagram and comparing the position according with the evaluation line (dotted line presented in fig. 8).

$$K_r = K_I / K_{mat} \quad (7)$$

where K_I – stress intensity factor calculated for the given case; K_{mat} – the fracture toughness of the material.

If $K_r = 1$, the failure is through brittle fracture.

$$S_r = \sigma_n / \sigma_f \quad (8)$$

where σ_n is the effective stress (following the analysis); σ_f is the resistance stress calculated as arithmetic average from yielding stress and ultimate stress resistance of the material (ultimate tensile resistance) :

$$\sigma_f = (f_y + f_u)/2 \quad (9)$$

where f_y is the yielding strength of the material and f_u is the ultimate limit strength.

If $S_r = 1$ then is resulting a plastic failure.

If the evaluation point (K_r, S_r) is situated in the domain (below the evaluation line), the dimension of the crack / flaw is considered acceptable. If the evaluation point is situated above the evaluation line, the defect is considered unacceptable.

The methodology can be used in a large spectrum of structures for assessing the defects and conclude upon the structural integrity.

The phases of the assessing of the known flaw can be considered as following:
1. Identification of the crack type; 2. Establishing the relevant data regarding the analyzed structure; 3. Determining the crack geometry; 4. Evaluation of the possible degradation mechanisms and the speed of the degradation; 5. Determining the crack maximum dimension for the failure modes; 6. Based on the speed of degradation, it is evaluated if the crack would grow to a maximal dimension in the

remaining lifetime or is needed to have additional inspections in order to monitor the crack growth; 7. It is examined the failure consequences; 8. Maintaining the flaw under the maximal size, including the safety coefficients.

4. Study case – Risk Based Analysis of a Steel Shell Structure

In a research program, together with the Faculty of mechanical Engineering of Belgrade, it was assessed the risk of failure considering the fracture mechanics approach for a steel shell structure part of a billboard tower [5].

Considering that the structure design project was applied by the owner of the tower (a multinational company), in different countries with respecting each country design requirements, an in depth assessing of the structure was needed in order to conclude about the structure reliability.

The structure has two components: the column which is a 1680 mm diameter S355J2 steel quality tube and the head of the tower where the billboard is fixed. The head is made of a truss system in order to undertake the dead and wind loads and to transmit them directly to the pillar (Figure 9).

The pillar is made of four sections – from the base to the top: Tube 1680 x 20 mm – 7m, Tube 1680 x16mm – 8.00 m, Tube 1680 x 12 – 7.00 m and Tube 1680 x 10 – 8.00 m. The sections are connected by bolted endplate joints.

The main loads events of the tower consists in wind loads from august 2009 until august 2016. A detailed wind load data was provided by the National Institute of Meteorology and Hydrology (INMH).

Applying a methodology for assessing the safety for a structure requires the knowledge of the base material from which the structure was build.

The research program consisted in:
- conventional testing: chemical analysis of the steel composition, traction tests , Charpy V-notch test, in order to determine the amount of energy absorbed by a material during fracture;
- fracture mechanics testing: determining the J integral curve, the fatigue crack growth.

The main concern was the joint between the segments of the tower.

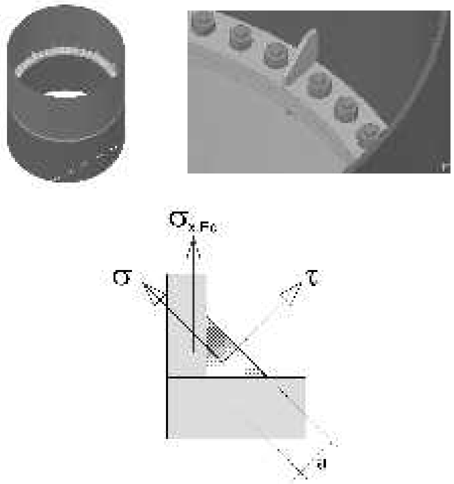


Fig. 9. *(a) Segment joint – view; (b) Welded joint between steel shell element and the endplate of the bolted connection*

For the risk based analysis of the welded joint were used the values of the calculated stress intensity factors K_{IC} =81.8 MPa·m$^{1/2.}$

Following the structural analysis and the design of the shell elements [6], in the area of the joint was calculated a stress

$\sigma_{\perp}$ = 161.2 MPa.

Regarding the crack geometry, the assessment was done with following data:

a = 10mm

w = 25.6 mm

where *a* is the length of the crack (which in this case is equal with the thickness of the welding) (Figure 9) and *w* is the thickness of the material in the direction of the crack propagation.

The crack being an edge crack, for the given geometry, according with Figure 6, it results a correction factor Y = 1.22 (a/b ≈ 0.40).

According with (4), for the given steel quality (f_y = 255 MPa; f_u = 510 MPa), it results K_I = 24.26 MPa·$m^{1/2}$, thus according with (7) K_r = 0.296.

In the reduced cross section of the cracked element, with the remaining cross section of 61 % from the total thickness (a / w = 0,39 –>the remaining cross section is 61%), is conservatively calculated the stress: $\pm_n = \pm_\perp / 0.61$ = 265 MPa.

According with (8), the parameter Sr results:

$S_r = \sigma_n / \sigma_f$ = 265 / [(355+510)/2] = 0.612

Finally the point (K_r, S_r) has the following coordinates: K_r=0.296; S_r=0.612.

The failure assessment diagram point position is indicated din Figure 10.

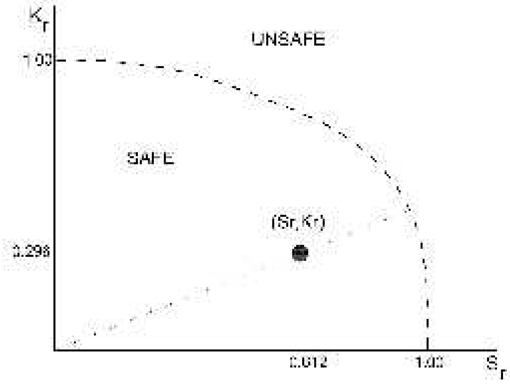


Fig. 10. *FAD for the given case*

The assessing procedure concludes that the joint is on the safe side.

5. Conclusions

The present civil engineering design norms are not considering the need of fracture design for structural elements. The standards are presenting conservative approaches and are not considering presence of flaws. In case of a detected flaw a structure or a structural element may be considered as a failed element and shall be replaced or strengthen. These decisions are taken usually in a conservative regime.

The fracture mechanics approach is taken into account the presence of a flaw as a prerequisite. It can be assessed and determined the life safety of an element or a structure, thus determining the ensured life duration.

The present paper describes an algorithm for risk assessing analysis using fracture mechanics approach.

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