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FRACTURE MECHANICS APPLIED ON INVESTIGATION OF THE EXISTING LATTICE STEEL STRUTURES

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Abstract: *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 assessed.*
An Engineering Critical Assessment (ECA) is an analysis, based on fracture mechanics principles, of whether or not a given flaw is safe from brittle fracture, fatigue, creep or plastic collapse under specified loading conditions.
An ECA can also be used to assess the significance of growing flaws, e.g. fatigue, creep or stress corrosion cracks, in order to make decisions on life extension and safe inspection intervals.
The present paper is referring to electricity transportation structures with truss type element – assessing procedures and evaluating the structural integrity according with fracture mechanics principles.

Key words: *fracture mechanics, lattice structures, structural integrity*

1. Introduction

The structural integrity and the evaluation of the remaining lifetime for a structure can be considered as mandatory procedure in the assessment of a structure.

In case of lattice steel structures, existing of flaws in critical parts of structural elements may lead to failures of the elements and in case of lack of redundancy, even to collapse of the entire structure.

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 [2].

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

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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 assessed Following the assessment can be concluded: the element of the structure needs to be repaired (the operation of the structure is forbidden in the actual circumstances), the element of the structure can operate until a time where a new assessment must be made. 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.

In case of electricity transportation lattice structures, in Romania, the designing lifetime is 40 years, and the structures are maintained with periodical inspections for corrosion protection following which some elements/part of elements are repainted.

From the structural point of view, these elements are presenting low redundancy – in case of an element failure (bracing), the structure can have the risk of collapse.

In case of cyclic loading – wind load and of maxim loading (extreme phenomena as storms or blizzards), some of these type of structures have failed/collapsed. Following the post factum assessment, it resulted that the principal causes where the existing of notch type flaws corroborated with corrosion type flaws acting on bracing elements (surface type flaws).

It is well known the case of the 2016 storm in Iernut (Mureș county), in which six 400kV lattice columns, four 220 kV lattice columns and eighteen 110kV type columns collapsed, thus leaving without electricity ten cities in Mureș county (Figure 1 and 2).

Fig. 1. *LEA type lattice steel column – bracing element failure*

Fig. 2. *LEA type lattice steel column – collapse following the storm*

2. Assessment Procedure

For an analysis of a known flaw, the following information is needed:

- size, position and orientation of flaw,
- stresses acting on the region containing the flaw,
- toughness and tensile properties of the region containing the flaw,

Elaboration of a methodology for determining the acceptability of detected cracks/flaws 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) [3,4].

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;
- *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;

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.

There are three levels of fracture assessment:

a) *Level 1* is a simplified assessment method applicable when the information on materials properties is limited.

b) *Level 2* is the normal assessment route.

c) *Level 3* is appropriate for ductile materials and enables a tearing resistance analysis to be performed.

Assessment is generally made by means of a failure assessment diagram (FAD) based on the principles of fracture mechanics. The vertical axis of the FAD is a ratio of the applied conditions, in fracture mechanics terms, to the conditions required to cause fracture, measured in the same terms. The horizontal axis is the ratio of the applied load to that required to cause plastic collapse. An assessment line is plotted on the diagram. Calculations for a flaw provide either the co-ordinates of an assessment point or a locus of points.

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 S_r (high yield strength), the presence of even a small crack is likely to trigger fracture.

3. Case Study – Assessment of a LEA Type Lattice Steel Structure

The applied method for structural integrity assessment is level 1 – Failure Assessment Diagrams type 1. This can be applied in situations in which there are limited information regarding the material or/and the stresses.

Conservative estimates of applied stress, residual stress and fracture toughness are employed. Additional partial safety factors are not used.

The area bounded by the axes and by the assessment line is a rectangle.

The flaw is acceptable if K_r or δ_r is less than $1/\sqrt{2}$ (i.e. 0.707) and S_r is less than 0.8.

A single FAD is used. If the assessment point lies in the area within the assessment line, *the flaw is acceptable*; if it lies on or outside the line, *the flaw is not acceptable*.

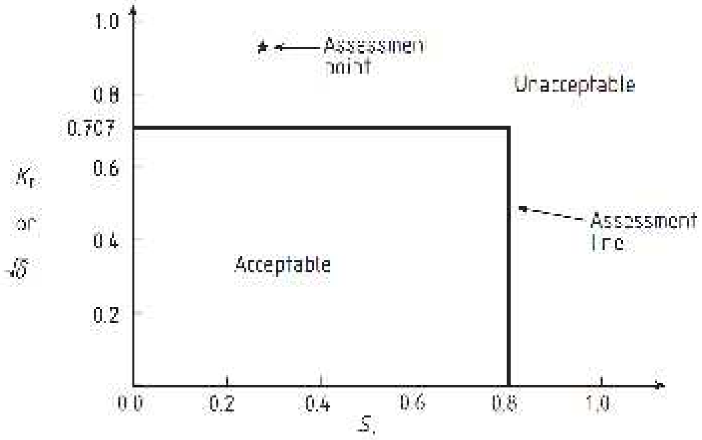


Fig.3. *FAD-1 assessment [1]*

Where a measured fracture toughness (as given by K_{mat} or δ_{mat}) is not available, an estimate of K_{mat} determined from Charpy V-notch impact test data may be used. The BS 7910 / 2013 [1] standard is proposing the following relation:

$$K_{mat} = \frac{12\sqrt{C_V} - 20}{(25/B)^{1/4}} + 20 \tag{1}$$

in which:

K_{mat} – represents the estimated inferior limit of fracture toughness [$MPa \cdot m^{1/2}$]

B – the thickness of the material for which the estimation of K_{mat} is requested [mm]

C_v – Charpy energy determined at service temperature [J].

The simplified level 1 assessment procedure which is needed to assess the *acceptability of a flaw* (in base metal or in weld joint), has the following steps:

Phase 1 - Through a structural analysis it is calculated the maximum stress in the assessed element.
Phase 2 - It is determined the fracture toughness throughout the K, J and δ parameters.
Phase 3 - It is determined the *fracture ratio (*K_r or δ_r*)*.

Fracture ratio K_r – the ratio of the stress intensity factor K_I, to the fracture toughness K_{mat} with the applied stress intensity factor, K_I.

$$K_r = K_I / K_{mat} \tag{2}$$

where K_{mat} represents the fracture toughness of analysed element material determined for the in service temperature.

The stress intensity factor (SIF) – K_I is determined with the following relation:

$$K_I = (Y \cdot \sigma) \cdot (\pi \cdot a)^{1/2} \tag{3}$$

where $Y \cdot \sigma = M \cdot f_w \cdot M_n \cdot \sigma_{max}$ depends on flaw type (according to annex M – BS7910 / 2013 [1]), M and f_w are bulging correction and finite width correction factors respectively; σ_{max} is the maximum tensile stress and M_m is a stress intensity magnification factor.
Phase 4 - It is determined the *load ratio (*S_r*)*.

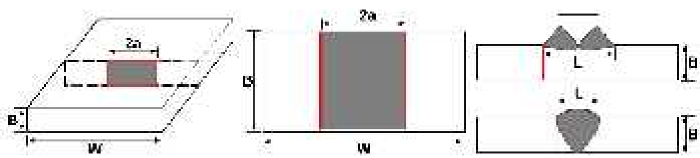
The load ratio, S_r, is calculated from the following equation:

$$S_r = \frac{\sigma_{ref}}{\sigma_f} \tag{4}$$

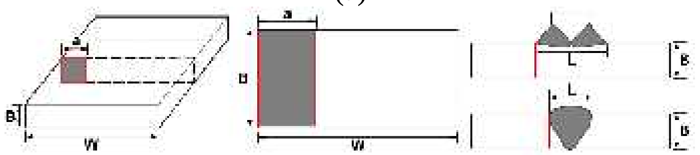
Where σ_{ref} is obtained from an appropriate reference stress solution given in Annex P of BS 7910/2013 [1]. The flow strength, σ_f, should be assumed to be the arithmetic mean of the yield strength and the tensile strength up to a maximum of $1.2 \cdot \sigma_Y$.

For study case, were done several assessments. It were chosen two types of flaws (Figure 4 a and b):

- Flat plate through-thickness flaw
- Flat plate edge flaw.



(a)



(b)

Fig. 4. *Idealizing of flaws for a flat plate – (a) through-thickness flaw (b) edge flaw*

Case of flat plate through-thickness flaw

For the calculation of SIF, $K_I = (Y\cdot\sigma)\cdot(\pi\cdot a)^{1/2}$ where $Y\cdot\sigma = M\cdot f_w\cdot M_n\cdot\sigma_{max}$.
According with BS7910 / 2013 M.3.1 [1]:

$$M = M_m = M_b = 1 \tag{5}$$
$$f_w = [\sec(\pi a/W)]^{1/2} \tag{6}$$

In order to determine δ_r parameter – the fracture ratio, for assessment can be used a path based on CTOD values.

Determining the ratio S_r based on relation $S_r = \sigma_{ref} / \sigma_f$, in which the reference stress is calculated according to BS7910 / 2013 P.3.1 [1]:

$$\sigma_{ref} = \frac{P_b + \left(P_b^2 + 9P_m^2\right)^{0.5}}{3\left[1-\left(\frac{2a}{W}\right)\right]} \tag{7}$$

It is calculated the yielding stress σ_f according with relation ($\sigma_f = (f_y + f_u)/2$ - *flow stress*), for which is needed the characteristics of the material (yielding and ultimate resistance).

Case of flat plate edge flaw

According with BS7910 / 2013 M.3.5 [1]:
For $a/W < 0,6$

$$M = 1;\ f_w = 1 \tag{8}$$
$$Mm = Mb = 1,12-0,23(a/W)+10,6(a/W)^2-21,7(a/W)^3+30,4(a/W)^4 \tag{9}$$

Determining the ratio S_r based on relation $S_r = \sigma_{ref} / \sigma_f$, in which the reference stress is calculated according to BS7910/2013 P.3.5 [1]:

$$\sigma_{ref} = \frac{P_b + \left(P_b^2 + 9P_m^2\right)^{0.5}}{3\left[1-\left(\frac{a}{W}\right)\right]} \tag{10}$$

For both cases (through thickness and edge flow), the point of assessment S_r and K_r is represented on FAD. The conclusions can be made base on the position of the points (Figure 3).

In case of assessment level 1 – FAD-1, there were done assessments on different flaws type and flaws positon for the in case – LEA type lattice steel column. The toughness value of 81,8 MPa·m$^{1/2}$ was determined on the specimens and was used in the assessment. A primary stress of 251 MPa was determined following the structural analysis.

Flaw cases description Table 1

Case no.	Name	Flaw type	Description of the flaw
Case 1	(TTF-1)	through thickness flaw	Crack in the brace in the proximity of the welded joint
Case 2	(TTF-2)	through thickness flaw	Crack in the welding longitudinal direction
Case 3	(TTF-3)	through thickness flaw	Crack in the welding transversal direction
Case 4	(TTF-4)	through thickness flaw	Crack in the brace in proximity of the welding longitudinal direction
Case 5	(TTF-5)	through thickness flaw	Crack in the brace joint in proximity of the welding transversal direction
Case 6	(EF-1)	edge flaw	Crack in the brace in the proximity of the welded joint
Case 7	(EF-2)	edge flaw	Crack in the welding longitudinal direction
Case 8	(EF-3)	edge flaw	Crack in the welding transversal direction
Case 9	(EF-4)	edge flaw	Crack in the brace in proximity of the welding longitudinal direction
Case 10	(EF-5)	edge flaw	Crack in the brace joint in proximity of the welding transversal direction

Following calculations according to the above presented procedure, the results are represented in tables 2, 3 and graphically in Figure 5.

FAD 1 – TTF type flaws – results Table 2

Through thickness flaw - TTF									
Case	B	W	$2a$	P_b	P_m	σ_{ref}	σ_f	S_r	K_r
	mm	mm	mm	MPa	MPa	MPa	MPa		
TTF-1	16	200	30	0	251	295.29	432.50	0.68	0.6755
TTF-2	32.63	200	30	0	251	295.29	432.50	0.68	0.6755
TTF-3	200	32.63	10	0	251	361.91	432.50	0.84	0.4085
TTF-4	25	200	30	0	251	295.29	432.50	0.68	0.6755
TTF-5	25	120	30	0	251	334.67	432.50	0.77	0.6931

FAD 1 – EF type flaws – results Table 3

Edge flaw - EF									
Case	B	W	a	P_b	P_m	σ_{ref}	σ_f	S_r	K_r
	mm	mm	mm	MPa	MPa	MPa	MPa		
EF-1	16	200	15	0	251	271.35	432.50	0.63	0.7688
EF-2	32.63	200	15	0	251	271.35	432.50	0.63	0.7688
EF-3	200	32.63	15	0	251	464.56	432.50	1.07	1.6678
EF-4	25	200	15	0	251	271.35	432.50	0.63	0.7688
EF-5	25	120	15	0	251	286.86	432.50	0.66	0.8139

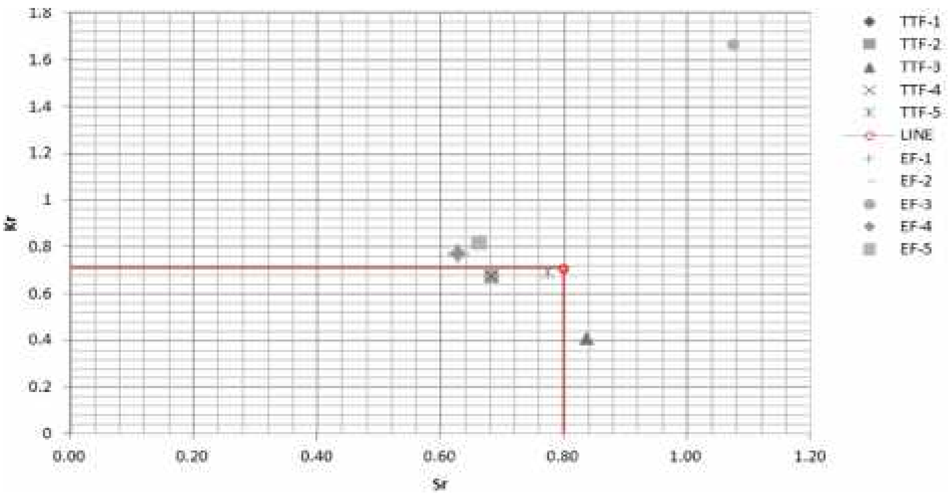


Fig. 5. *FAD – 1 plotted results*

4. Conclusions

In the assessed cases of thickness through flaw, for the given dimensions (geometry of the element and the crack), the structure is on the safe side according to the failure assessment diagrams level 1 – FAD-1, with one exception TTF-3 case. This is caused by the high value of S_r – the element (joint) is sensible in the area of the weld. High value of the main stress and the given crack size, makes the joint to fracture.

The edge flaw type case are presenting different conclusions – the assessing FAD-1 reveals an over limit of all cases. The K_r fracture ratio is higher than 0.707 and in case EF-3 the S_r is also over limit;

The engineering critical assessment (ECA) can conclude that there is a high risk of fracture for the given element (bracing) joint [5].

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