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Sensitivity of Engineering Critical Assessmentof Through-Thickness Axial Flaws on Pressure Equipment

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Abstract **– This paper deals with a sensitivity analysis of engineering critical assessment, using a fracture assessment diagram of through-thickens axial flaws on pressure equipment. Basic option calculations are performed per BS 7910, using engineering fracture mechanics principles, followed by the provision of assessment points. For evaluation purposes, arbitrary design properties of pressure equipment and temperature-dependent materials properties were used. Several through-thickness axial flaw sizes were used for critical assessment. Furthermore, the sensitivity of critical assessment is evaluated by varying stress states and material fracture toughness. Finally, the sensitivity analysis shows how axial flaw growth may become critical, or its acceptability, depending on varying stress states and temperature-dependent material properties, on selected pressure equipment.**

Keywords **– Critical assessment, axial flaw, pressure equipment, sensitivity analysis, fracture mechanics.**

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1. Introduction

Pressure equipment, such as vessels and pipelines, are designed to contain the pressure and withstand various loads during their lifetime. There are international design and manufacturing codes and regulation requirements for new equipment, which can be considered as a good-engineering-practice (GEP), but there is also a well-known approach regarding the evaluation of existing pressure equipment, based on fracture mechanics, called fitness-for-service (FFS).

Both GEP and FFS consider two important concepts: yield-before-the-break (YBB) and leak-before-the-break (LBB) [1], [2]. Also, while GEP considers homogenous material and the absence of faults, such as cracks, the FFS is based on stipulated or existing material faults. During its lifetime pressure equipment may suffer from various material degradation mechanisms, such as corrosion, fatigue, and creep, which may lead to crack initiation and growth, and inevitable failure [3], [4], [5]. Principally, both YBB and LBB concepts are assured with sufficient material strength and particularly toughness [1], [6]. Specifically, LBB is required for the nuclear, oil, and gas industry, i.e. generally for pressure equipment [2], [10]. The LBB is considered as crack growth through the thickness of the equipment shell or pipe wall, which will generate a detectable leak of a product, while the material still possesses sufficient toughness to provide stable crack growth in a time frame for satisfactory application of an FFS and additional intervention, such as repair. Otherwise, if crack growth reaches its critical size, unstable brittle growth, rupture and failure of equipment are unavoidable.

Without neglecting importance of detailed and rigorous procedures for the LBB concept defined in assessment standards, such as BS 7910 [7] and other literature [2], [8], [9], [10], this paper intends to provide a sensitivity analysis of influential variables on engineering critical assessment (ECA) for FFS, for stipulated axial through thickness flaws on pressure equipment. Variables which determine an ECA outcome, based on fracture mechanics and corresponding failure assessment diagrams (FAD), are flaw size (its length), material strength and toughness, and stress state.

2. Considered Geometry and Stress States

The pressure equipment geometry and two reference stress states are considered as shown in Figure 1. Regarding provided design values of pressure equipment, the allowable stress $\sigma_a=0.72\times Y$ (Y is yield stress), is considered due to the selected steel grade with a design yield stress Y=355 MPa, while a detailed analysis of material properties is discussed in the following paragraph. The factor 0.72 for allowable stress is selected as the common one concerning the requirements of various design codes for pressure equipment [11]. Specific radiuses r_0, r_i and r_m are derived from D_0 and B (Figure 1). Two load conditions with corresponding pressure levels p are considered, nominal (n) and high (h); which give two levels of hoop stress σ_h in the pressure equipment shell or pipe wall.

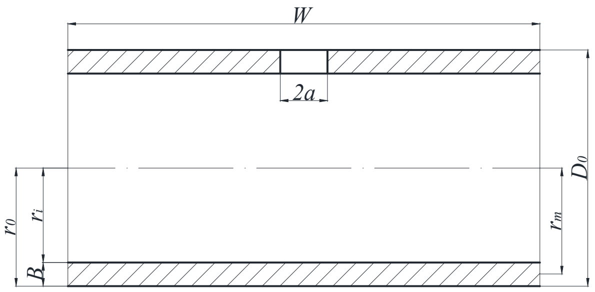

Figure 1. Pressure equipment geometry

Table 1. Through-thickness axial flaw and reference stress states

W (mm)	2,000
B (mm)	6
D_0 (mm)	600
Y (MPa)	355
σ_a (MPa)	256
p_n (bar) / $\sigma_{h\text{-}n}$ (MPa)	40 / 200
p_n (bar) / $\sigma_{h\text{-}h}$ (MPa)	50 / 250
σ_a/Y	0.72

It will be shown that in accordance with BS 7910 [7], for the calculation of stress intensity factors K, as well as reference stress σ_{ref}, the length of equipment W (as the finite length for the vessel) could be neglected, since bending stress is neglected. In addition, two operating temperatures T are considered due to their influence on mechanical properties, namely room temperature (RT, +20 °C) and low temperature (LT, -40 °C).

3. Material Properties

While the design process uses design material properties according to the design code [11] and material specification [12], an ECA should be performed with real material properties (determined by destructive testing or obtained from the material certificate). However, real material properties must be equal to or higher than design ones, otherwise, there is doubt regarding material quality. Also, it is well known that temperature has a detrimental influence on the mechanical properties of steel, particularly affecting toughness at low temperatures. This is shown in Figure 2 for various steel grades in the form of plates and pipes, all with Y=355 MPa, but in different delivery conditions (N – normalized, M – thermo-mechanically treated, Q – quenched and tempered). There, the notation "355" represents the common European standard plate and pipe grade, while "X52" represents the common American standard pipe grade.

Real impact toughness values KV shown in Figure 2, are taken from the literature [5], [13], [14] and own research [15], [16] and fitted accordingly. The notation "min" corresponds to the design values (minimum required as per material specification standards) [12].

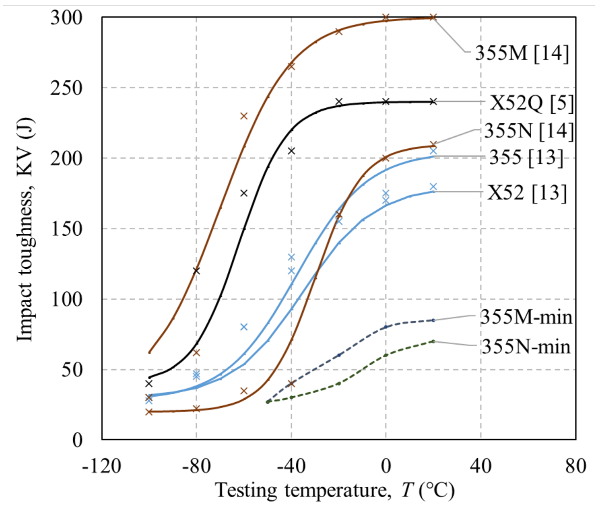

Figure 2. Influence of testing temperature on impact toughness of 355 steel grade, fitted according to [16]

Regarding the influence of low temperature on yield stress σ_Y and tensile strength σ_U, there is a known approach for estimation as per BS 7910, described by equations (1) and (2), where "RT" stands for room temperature and "LT" for low temperature. [7]

$$\sigma_{\text{Y-LT}} = \sigma_{\text{Y-RT}} + 10^5 \cdot (491 + 1.8 \cdot T)^{-1} - 189 \quad (1)$$

$$\sigma_{\text{U-LT}} = \sigma_{\text{U-RT}} \left(0.7857 + 0.2423 \cdot e^{(-0.00586 \cdot T)}\right) \quad (2)$$

Real mechanical properties of selected 355-grade steel required for further ECA are given in Tables 2 and 3. Real values of impact toughness KV are used for the calculation of both upper (US) and lower shelf (LS) of K_{mat}, that is further used for ECA (FAD) according to BS 7910. This is described by equations (3) and (4) [7], [16].

$$K_{\text{mat-US}} = \sqrt{\frac{E \cdot \left(0.53 \cdot KV_{\text{US}}^{1.28}\right)\left(0.2^{0.133 \cdot KV_{\text{US}}^{0.256}}\right)}{1{,}000 \cdot \left(1 - \nu^2\right)}} \quad (3)$$

$$K_{\text{mat-LS}} = 0.54 \cdot KV_{\text{LS}} + 55 \quad (4)$$

In equation (4) E is Young's modulus and υ is the Poisson's ratio.

Table 2. Strength at RT and LT

Temperature	Strength (MPa)	
	σ_Y	σ_U
RT (+20 °C)	410	495
LT (-40 °C)	460 [1]	541 [2]

Table 3. Toughness at RT and LT

Temperature	KV (J)	K_{mat} (MPa×m$^{0.5}$)
RT (+20 °C)	210 (US)	220 [3]
LT (-40 °C)	40 (LS)	77 [4]

4. Stress Intensity Factors

The precise calculation as per BS 7910 [7] of stress intensity factor K considers the contribution of primary stress (hoop or membrane and bending stress) and secondary (residual) stresses. However, for simplification purposes, further assessment of K considers only hoop stress σ_h (two levels values are shown in Figure 1), while bending (as primary) and residual (as secondary) stresses are neglected. Thus, the simplified stress intensity factor K can be calculated as:

$$K = F \cdot \sigma_h \sqrt{a \cdot \pi} \quad (5)$$

In equation (5) F stands for dimensionless correction factor, while a is crack half-length as shown in Figure 1. There are several concepts for the calculation of factor F. For further discussion purposes, the four concepts are selected and correspondingly noted:

1. **BS**: BS 7910 (Paragraph M.7.2.1, Curved shells containing axial flaws – Through thickness flaws oriented axially) [7],
2. **SI**: SINTAP (Stress intensity factor Handbook, Axial trough thickness defects in cylinders) [17],
3. **AS**: ASM Handbook 19, Fatigue and Fracture, Axial cracks in hollow cylinders [18],
4. **FG**: Gajdos (Evaluating the integrity of pressure pipelines by fracture mechanics) [19].

Besides the same major equation (5) for the calculation of K, there are other similarities as well as some major differences. All concepts use ratio λ as defined by equation (6), except BS that defines it by equation (7).

$$\lambda = a / \left(r_{\text{m}} \cdot B\right)^{0.5} \quad (6)$$

$$\lambda_{\text{BS}} = \left[12 \cdot \left(1 - \nu^2\right)\right]^{0.25} \cdot a / \left(r_m \cdot B\right)^{0.5} \quad (7)$$

BS concept restricts the range of application for 0≤λ≤12.211 and $5 \le r_{\text{m}}/B \le 100$. Both BS and SI concepts consider the distribution of stress intensity factor K along the outer and inner surface equipment shell (wall), while such an approach does not exist within AS and FG concepts. Higher values for BS ad SI concepts are considered further, which correspond to the outer surface of the equipment shell (wall). Within BS, factor F is equal to the sum of factors which must be read from BS 7910 (originally [7], marked as M1 and M2, from tables M.1a and M.1b), depending on values λ and r_{m}/B. The SI concept provides calculations of factors which are not given here due to their length (originally [17] marked as G1 and g1). It seems that both concepts BS and SI are similar but with minor differences in the final value of F. Contrary, AS and FG concepts use a bit simplified approach, which is defined by the equations (8) and (9) [18], [19].

$$F_{\text{AS}} = \left(1 + 0.52 \cdot \lambda + 1.29 \cdot \lambda^2 - 0.074 \cdot \lambda^3\right)^{0.5} \quad (8)$$

$$F_{\text{FG}} = \left(1 + 1.255 \cdot \lambda^2 - 0.0135 \cdot \lambda^4\right)^{0.5} \quad (9)$$

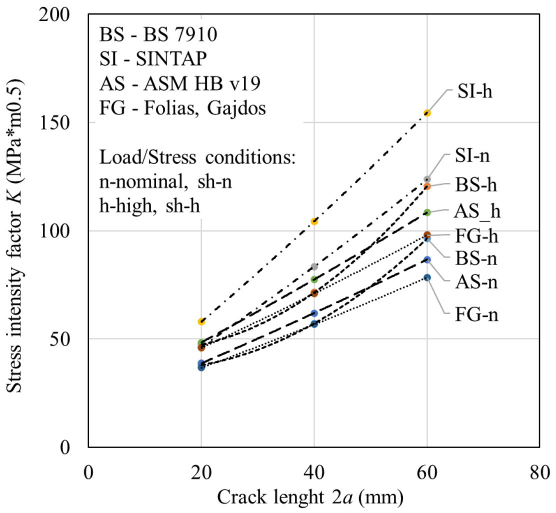

Figure 3. Stress intensity factors

Figure 3 gives an analysis of stress intensity factors K calculated according to mentioned four concepts for three arbitrary through-thickness axial flaw (crack) lengths of 20 mm, 40 mm and 60 mm.

5. Fracture Assessment Diagram

The fracture assessment diagram (FAD) for ECA consists of calculation of coordinates of assessment points (AP) for K_r and L_r, and the provision of a failure assessment line (FAL) with two extreme cases, namely brittle fracture (for K_r=1) and plastic collapse (L_r=$L_{r,max}$), with its theoretical borderlines on coordinates L_r=0.62 for brittle fracture (BF) and L_r=0.95 for plastic collapse (PC) [7], [20].

Thus, if AP lies beneath FAL certain level of safety and avoidance of fracture is achieved, while different AP for different crack sizes may be interpreted as stable crack growth. Otherwise, if AP lies above FAL failure is obvious, and crack growth is considered as unstable. With consideration of previously mentioned assumptions regarding stress state, the coordinates K_r and L_r can be determined by equations 10a and 10b.

$$K_r = \frac{K}{K_{mat}} \tag{10a}$$

$$L_r = \frac{\sigma_{ref}}{\sigma_Y} \tag{10b}$$

In equation (10b) σ_{ref} is the reference stress, which is calculated as per BS 7910 using factor M in the function of crack length, according to equations (11) and (12), while r_i and B are defined in Figure 1 [7].

$$\sigma_{ref} = 1.2 \cdot M \cdot \sigma_h \tag{11}$$

$$M = \left[1 + 1.6 \cdot \left(\frac{a^2}{r_i \cdot B}\right)\right]^{0.5} \tag{12}$$

Provision of FAL, i.e. $f(L_r)$, is based on the equations (13a-13d) as per BS 7910 [7].

$$f(L_r) = \left(1 + \frac{L_r^2}{2}\right)^{-0,5} \quad \text{for} \quad L_r < 1 \tag{13a}$$

$$f(L_r) = \left(\lambda + \frac{1}{2\lambda}\right)^{-0,5} \quad \text{for} \quad L_r = 1 \tag{13b}$$

$$f(L_r) = f(1) \cdot L_r^{(N-1)/2N} \quad \text{for} \quad 1 < L_r < L_{r,max} \tag{13c}$$

$$f(L_r) = 0 \quad \text{for} \quad L_r \geq L_{r,max} \tag{13d}$$

Where λ, N and $L_{r,max}$ can be calculated by equations (14a-14c).

$$\lambda = 1 + E \cdot \Delta\varepsilon / R_{el} = 1 + E \cdot \Delta\varepsilon / \sigma_Y \tag{14a}$$

$$N = 0.3 \cdot \left(1 - \sigma_Y / \sigma_U\right) \tag{14b}$$

$$L_{r,max} = \left(\sigma_Y + \sigma_U\right) / 2\sigma_Y \tag{14c}$$

Here, $\Delta\varepsilon$ is the extent of Luder's strain for steel 355 grade with discontinuous yielding (σ_Y is at R_{eL}), estimated to be 0.022 at RT, and 0.020 at LT [7].

The AP coordinates for all three crack sizes are calculated by equations (10a) and (10b). Two FAL are calculated by equations (13a) to (13d) for two temperatures (RT and LT), due to the difference in strength properties σ_Y and σ_U.

Summarized conditions and corresponding AP coordinates are given in Tables 4 and 5 for room temperature and low temperature, respectively.

Table 4. Conditions and corresponding AP coordinates (Lr, Kr) for three crack sizes at RT

a (mm)	K_{mat}=220 MPa×m$^{0.5}$ and σ_Y=410 MPa			
	Nominal load / stress 40 bar / 200 MPa		High load / stress 50 bar / 250 MPa	
	K_r	L_r	K_r	L_r
10	0.21	0.61	0.26	0.76
20	0.38	0.68	0.47	0.85
30	0.56	0.79	0.70	0.99

Table 5. Conditions and corresponding AP coordinates (Lr, Kr) for three crack sizes at LT

a (mm)	K_{mat}=77 MPa×m$^{0.5}$ and σ_Y=460 MPa			
	Nominal load / stress 40 bar / 200 MPa		High load / stress 50 bar / 250 MPa	
	K_r	L_r	K_r	L_r
10	0.60	0.55	0.76	0.68
20	1.09	0.61	1.36	0.76
30	1.61	0.70	2.02	0.88

Finally, FAD (all APs and FAL) is constructed and shown in Figure 4 for analysis and ECA. Some useful things can be noted for displayed cases:

- FAL in a zone close to plastic collapse may slightly change its position due to a change in strength properties.
- At room temperature, crack growth from 2*a*=20 mm to 2*a*=60 mm may seem to be safe and acceptable, or at least considered stable, for both nominal and high load stress conditions.
- However, only a crack with size 2*a*=20 mm is safe and acceptable at low temperature, i.e. at -40 °C, for both nominal and high load stress conditions.
- An increase in stress level from nominal to high moves AP closer (RT, h) and over (LT, h) FAL, where a crack may become inacceptable (intolerable, unsafe).
- All cases do not include safety margin or safety coefficient, which may be required for ECA.

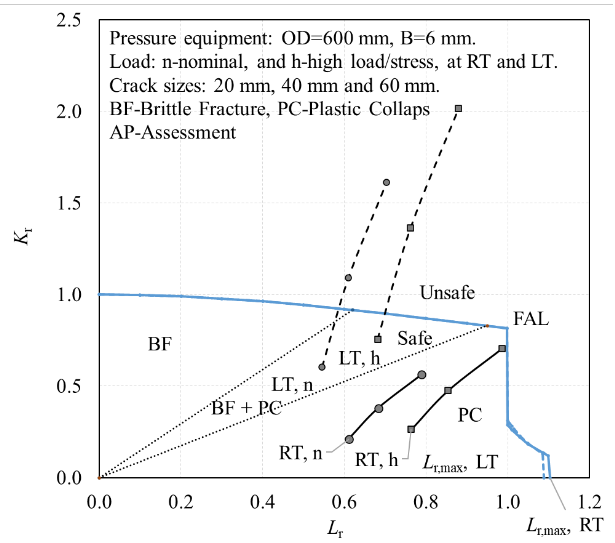

Figure 4. FAD/ECA of a through-thickness axial crack(s) in pressure equipment

The fracture mechanics triangle of properties plays major role in position of assessment point(s) and the final decision on safety.

It consists of (1) crack size, type, and position; (2) stress state and (3) material properties. This could be graphically represented as shown in Figure 5 if the growth or increase of each of the variables is considered.

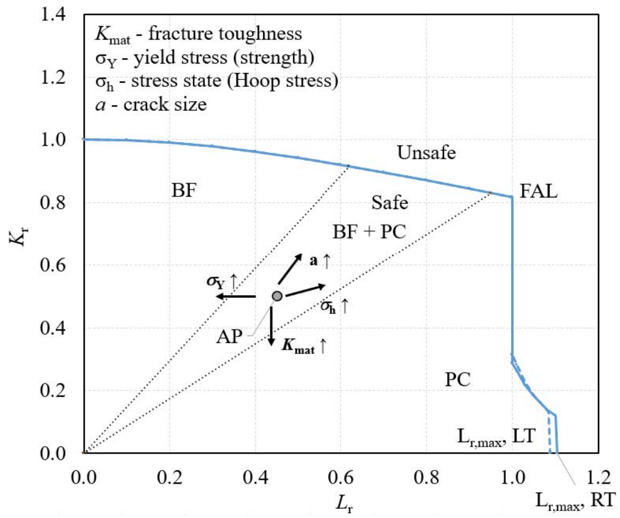

Figure 5. Generalized influence of variables on safe or unsafe AP position

6. Conclusion

Engineering critical assessment (ECA), using a fracture assessment diagram (FAD) represents a quite sensitive and delicate activity, where many variables may influence the outcome and proper interpretation. However, quite precise guidelines are available in reference assessment standards, such as BS 7910.

Interestingly, ECA is mainly intended for pressure equipment that is already in use, where regular and periodic inspection may detect various material faults and prevent failure. Nevertheless, it can be used as tool within the design stage of new equipment, where integrity assessment could be made (or conducted) for predicted or expected flaws in material.

If considering the existing equipment, where material properties are known and subject to change, the only solution to accommodate a favourable (i.e. safe) solution without risk is to decrease the stress state in material, meaning decrease operating parameters (e.g. pressure). However, that may not be always a rational or economical decision. Thus, a proper and periodical inspection for control of flaw growth is the only reasonable solution if the flaw dimensions are within acceptable (safe) limits.

On the other side, during the design stage there is certainly more options available. In this case, a decision regarding use of more appropriate material can still be made, ensuring adequate mechanical properties, particularly sufficient toughness. On the other side, there is still possibility to control the allowable stress state as well.

Therefore, a good estimation of possible loads or stress state(s), both primary and secondary, is of crucial importance.

Finally, the operational temperature may play an important role, because any changes in mechanical properties, both strength and toughness must be considered.

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