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Structural integrity of a wind loaded cylindrical steel shell structure

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Abstract

The structural integrity and life assessment can be considered as a mandatory request in the civil engineering designing and manufacturing process.

The paper is presenting the procedure for determination of crack acceptability based on fracture toughness with failure assessment methods (FAD-1 and FAD-2) which is applied to a cylindrical steel shell structure with welded joints which is having the wind as a main load.

The assessment is using BS7910/2013. Thus were assessed common types of flaws met at steel shell cylindrical structure elements using failure assessment diagrams – level 1 – FAD-1. The results are presenting the acceptability level for each type of flaw with comparative graphs, determining also the critical dimension of the flaw.

For each flaw was calculated the failure assessment diagram (FAD-2). Different comparisons between group of flaws were done, revealing the critical crack like flaw. Also the critical value of flaw dimensions were calculated for each flaw type. The methodology establishes clear rules for assessment of structural elements with cracks, determining the initial flaws, assessed flaws and critical values of the cracks.

Based on the detailed procedures described in the paper, on conclusions to the assessment done on each type of flaw, the assessment methods can be applied very easy in current design practice with different material characteristics

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Keywords: structural integrity, steel shell elements, engineering critical assessment;

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Nomenclature

k_t	stress concentration factor and
k_m	stress magnification factor due to misalignment
K_I	the stress intensity factor (SIF)
K_{mat}	the fracture toughness
M_m	stress intensity magnification factor
σ_Y	the yielding resistance of the material
σ_u σ_T	the ultimate resistance of the material
σ_{max}	the maximum tensile stress
$(Y{\cdot}\sigma)_P$	contribution of the main stresses
$(Y{\cdot}\sigma)_S$	contribution of the secondary stresses
Y	correction factor

1. Introduction

Most welding fabrication codes specify maximum tolerable flaw sizes and minimum tolerable Charpy energy, based on good workmanship, i.e. what can reasonably be expected within normal working practices. These requirements tend to be somewhat arbitrary, and failure to achieve them does not necessarily mean that the structure is at risk of failure. 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 therefore be used: *during design*, to assist in the choice of welding procedure and/or inspection techniques; *During fabrication*, to assess the significance of known defects which are unacceptable to a given code, e.g. EN1090-2 (2011), or a failure to meet the toughness requirements of a fabrication code; *During operation*, to assess flaws found in service and to make decisions as to whether they can safely remain, or whether down-rating/repair are necessary.

The ECA concept (also termed 'fitness-for-purpose analysis') is widely accepted by a range of engineering industries.

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,

The fact that knowledge of all these three aspects is necessary, implies a multidisciplinary approach, involving stress analysis, NDT expertise and materials engineering.

The analysis is carried out in accordance with the British Standard procedure BS 7910 (2013) (*'Guide to methods for assessing the acceptability of flaws in metallic structures*'). Although simplified analyses can be carried out based on code values of Charpy energy and maximum allowable stresses, it is usually necessary to carry out fracture-mechanics testing (critical *K, CTOD* or *J*) in order to obtain an accurate measurement of the material toughness. Additional stress analysis (e.g. by hand calculation or Finite Element Analysis) may also be required.

For design purposes, or for analysis of weldments which fail to meet a toughness requirement the ECA is based on a hypothetical '*reference flaw'* which is highly unlikely to be missed during inspection.

The case study of the paper presents the research on a steel shell element part of a billboard tower structure located in Romania – Brașov city. After erection in 2009, two inspections of the structure were performed by qualified personnel in order to assess the state of the structure. Following a visual investigation of the structural elements and the joints of the billboard tower, several cracks were discovered in the area of the segment joints of the tower.

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 1).

The column is made of four sections – from the base to the top: Tube 1680 x 20mm – 7m, Tube 1680 x16mm – 8,00m, Tube 1680 x 12 – 7,00m and Tube 1680 x 10 – 8,00m. 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).

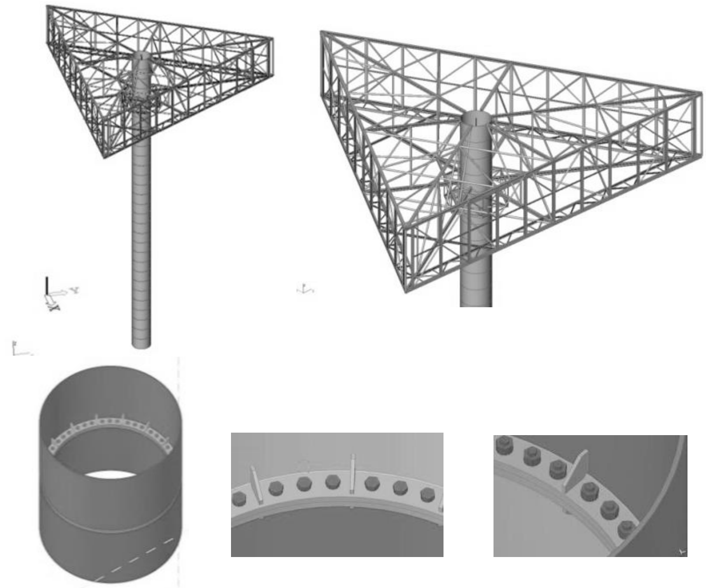

Fig. 1. Billboard tower – general views and segments joints views

2. Level 1 type assessment (FAD-1)

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

- Through a structural analysis it is calculated the maximum stress in the assessed element (Radu D. et al. – 2017). The used stress is the maximum tension stress σ_{max} which is equal with sum of the stress components. There are used only the nominal membrane stresses S_{nom} for which
$$\sigma_{max} = k_t \cdot S_{nom} + (k_m - 1) \cdot S_{nom} + Q \quad (1)$$
- It is determined the fracture toughness throughout the K, J and δ parameters.
- It is determined the *fracture ratio (K_r* or δ_r). K_r – the ratio of the stress intensity factor K_I, to the fracture toughness K_{mat} (3) with the applied stress intensity factor, K_I general form presented in formula 4.
$$K_r = K_I / K_{mat} \quad (2)$$
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:
$$K_I = (Y \cdot \sigma) \cdot (\pi \cdot a)^{1/2} \quad (3)$$
where $Y \cdot \sigma = M \cdot f_w \cdot M_n \cdot \sigma_{max}$ depends on flaw type (according to annex M – BS7910 / 2013), M and f_w are bulging correction and finite width correction factors respectively;.
- It is determined the *load ratio (S_r).* The load ratio, Sr, is calculated from the following equation:
$$S_r = \frac{\sigma_{ref}}{\sigma_f} \quad (4)$$
Where σ_{ref} is obtained from an appropriate reference stress solution given in Annex P of BS 7910/2013. 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 $1.2\sigma_Y$.

In case of assessment level 1 – FAD-1, there were done assessments on different flaws type and flaws positon for the in case – segment joint (figure 2). The toughness value of 81,8 MPa·m$^{1/2}$ was determined on specimens, following experiments, and was used in the assessment.

A primary stress of 251 MPa was determined following a linear elastic analysis (Radu D. et al., 2017) and confirmed through a FEM in depth analysis performed on a reduced model – only a segment joint (Milos Milosevic, 2016).

Ten cases were assessed. These are presented in table 1 and figure 2.

Following calculations according to the above presented procedure, the results are represented in table 2 and graphically in figure 3.

Table 1. Flaw cases description

Case no.	Name	Flaw type	Description of the flaw
Case 1	(TTF-1)	through thickness flaw	Crack in the tube wall 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 flange of the segment joint in proximity of the welding long. direction
Case 5	(TTF-5)	through thickness flaw	Crack in the flange of the segment joint in proximity of the welding transversal direction
Case 6	(EF-1)	edge flaw	Crack in the tube wall 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 flange of the segment joint in proximity of the welding long. direction
Case 10	(EF-5)	edge flaw	Crack in the flange of the segment joint in proximity of the welding transversal direction

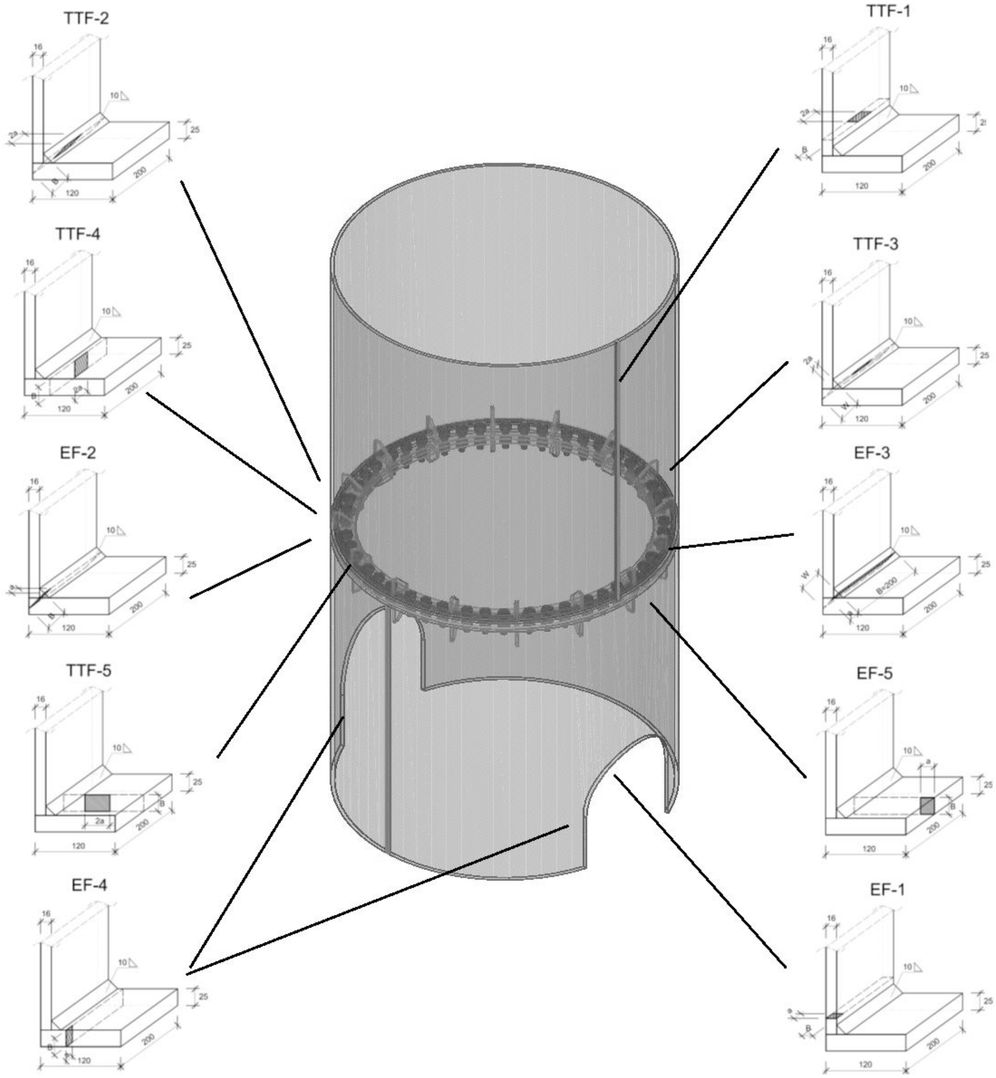

Fig. 2. FAD – 1 assessed flaw types - Typical flaws in a steel shell element and steel shell element joint

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 (Manjgo. M, 2010).

It can be noticed an approach to the assessment line for TTF5 case – crack in the flange of the segment of the joint – K_r value is close to 0.707.

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 flange of the segment joint is a critical part of the structure. This subassembly is subjected to high local stresses. The weld itself is not checking for edge flaws of 15mm which can be a common situation in the assessment of the joints.

The engineering critical assessment (ECA) can conclude that there is a high risk of fracture for the given segment joint in the area of the flange.

Table 2. FAD 1 – TTF and EF type flaws - results

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
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

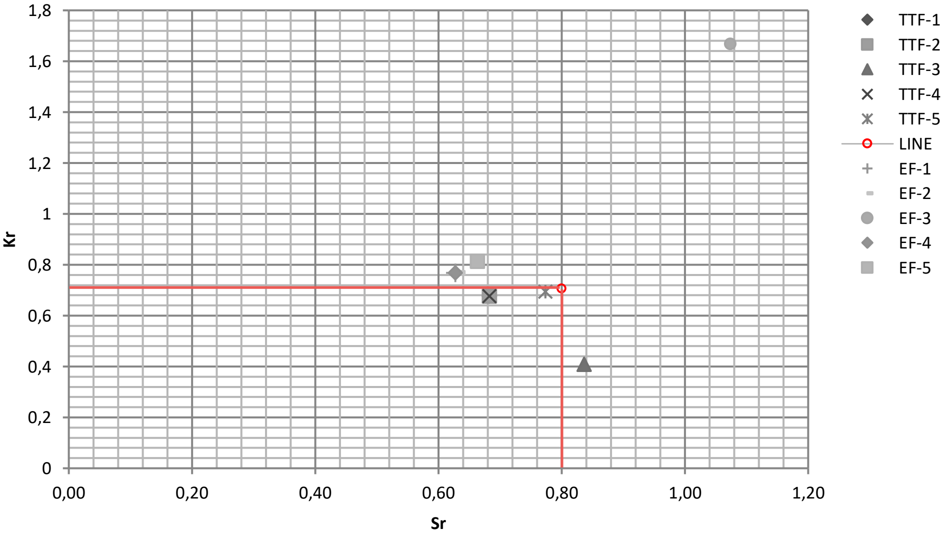

Fig. 3. FAD – 1 plotted results

3. Level 2 assessment – FAD-2

The level 2 assessment is the normal evaluation path for general application. The method is presenting an assessment line given by an equation of a curve and a cut-off line. If the assessment point is in the interior of the surface limited by the assessment line, the flaw is acceptable and if the assessment point is at the outside area, the flaw is considered unacceptable (BS7910 – 2013). The equations which are describing the assessment line are:

$$\sqrt{\delta_r}\ \ or\ \ K_r = \left(1-0{,}14L_r^2\right)\left[0{,}30+0{,}70\exp(-0.65L_r^6)\right] \text{ for } L_r \le L_{rmax} \tag{5}$$

$$\sqrt{\delta_r}\ \ or\ \ K_r = 0 \text{ for } L_r > L_{rmax} \tag{6}$$

The cut-of line is fixed in point where $L_r = L_{rmax}$ where:

$$L_{r\,max} = \left(\sigma_Y + \sigma_u\right)/\left(2\sigma_Y\right) \tag{7}$$

For the assessment on level 2 FAD is necessary to pass through the following phases (more or less similar with FAD-1). As presented at FAD-1, the stresses must be known – following a structural analysis, these can be determined. The assessments are considering the real distribution of the stresses in the proximity of the flaws – P_m, P_b, Q_m and Q_b. The stress intensity factor is determined as FAD-1 where for the level 2 the factor:

$$Y\cdot\sigma = (Y\cdot\sigma)_P + (Y\cdot\sigma)_S \tag{8}$$

in which:

$$(Y\cdot\sigma)_P = M\cdot f_w\cdot \{k_{tm}\cdot M_{km}\cdot M_m\cdot P_m + k_{tb}\cdot M_{kb}\cdot M_b\cdot [P_b + (k_m - 1)P_m]\} \tag{9}$$

$$(Y\cdot\sigma)_S = M_m\cdot Q_m + M_b\cdot Q_b \tag{10}$$

The correction factor Y is determined according to the level 1 relations function of the defect type (BS7910 – 2013). The ratio of stress L_r is determined according with:

$$L_r = \sigma_{ref} / \sigma_Y \tag{11}$$

in which σ_{ref} is obtain according with a relation specific with the flaw type.

The point/points of assessment are represented graphically in (K_r, L_r) coordinates on the FAD level 2.

In case of the assessment level 2 – FAD-2, there were done assessments on different flaws type and flaws positon for the in case billboard tower – steel shell element. The values of the input data are:

- σ_Y (yield strength)= 355 MPa; σ_T (ultimate strength)= 510 MPa; specific for S355J2 steel type;
- K_{mat} = 81,8 MPa·m$^{1/2}$ was determined on the specimens and was used in the assessment.
- P_m = 251 MPa - Primary stress which was determined following the structural analysis
- k_{tm} = 1; k_{tb} = 1 (stress concentrators factors)
- Q_{tm} = 0 (thermal membrane stress) and Q_{tb} = 0 (thermal bending stress)
- Q_m = 0 (residual membrane stress) and Q_b = 0 (residual bending stress)

The geometry (dimensions) of each assessed flaw is presented in table 3 together with the results (L_r and K_r values). A graphical representation of the assessment results are presented in figure 4 and 5.

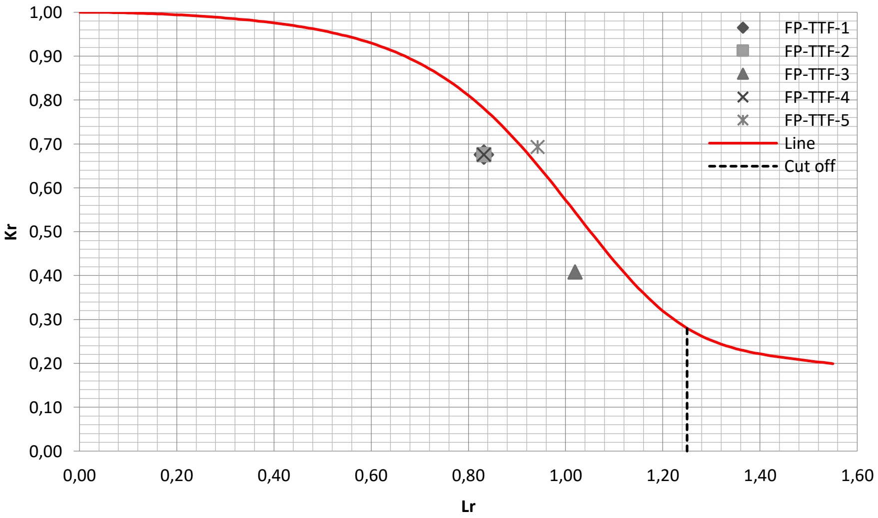

Fig. 4. FP-TTF – Group of flaws - assessment

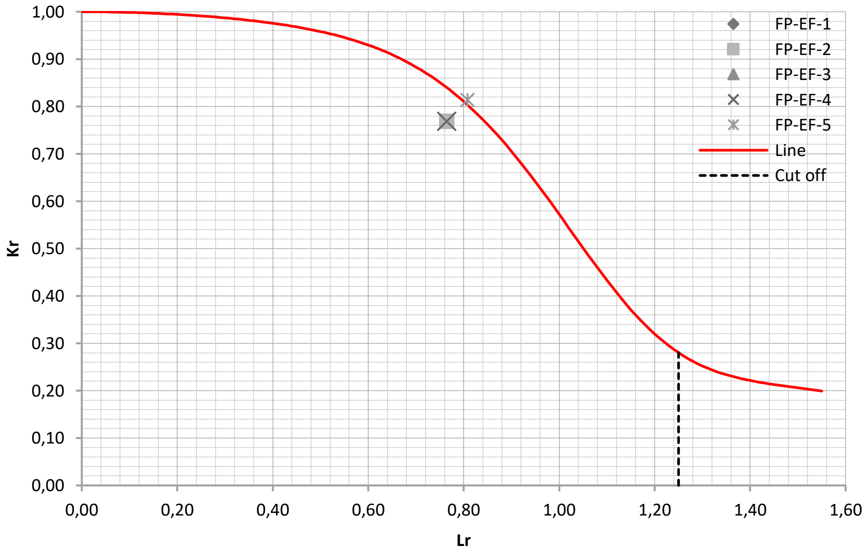

Fig. 5. FP-EF – Group of flaws – assessment

Table 3. FAD 2 – in case - flaws assed: geometry and results (with corresponding figures and flaw name – figure 6.17 and table 6.4)

Fig. no.	Case	B	W	2a	a	2c	p	r_0	h	t_w	L_r	K_r
		mm	*mm*	*mm*	*mm*	*mm*	*mm*	*mm*	*mm*	*mm*		
4	FP-TTF-1	16	200	30							0.8318	0.6755
	FP-TTF-2	32.63	200	30							0.8318	0.6755
	FP-TTF-3	200	32.63	10							1.0195	0.4085
	FP-TTF-4	25	200	30							0.8318	0.6755
	FP-TTF-5	25	120	30							0.9427	0.6930
5	FP-EF-1	16	200		15						0.7644	0.7688
	FP-EF-2	32.63	200		15						0.7644	0.7688
	FP-EF-3	200	32.63		15						1.3086	1.6678
	FP-EF-4	25	200		15						0.7644	0.7688
	FP-EF-5	25	120		15						0.8080	0.8139

4. Critical value of flaw dimension analyses for fracture assessment

Determining the critical value of the flaws (TWI CrackWise 5.0) is important because it serves to a limit value for fatigue further analysis based on fracture mechanics principles, needed for determining the number of cycles for a crack to extend from an initial dimension to a critical dimension which means the failure of the element.

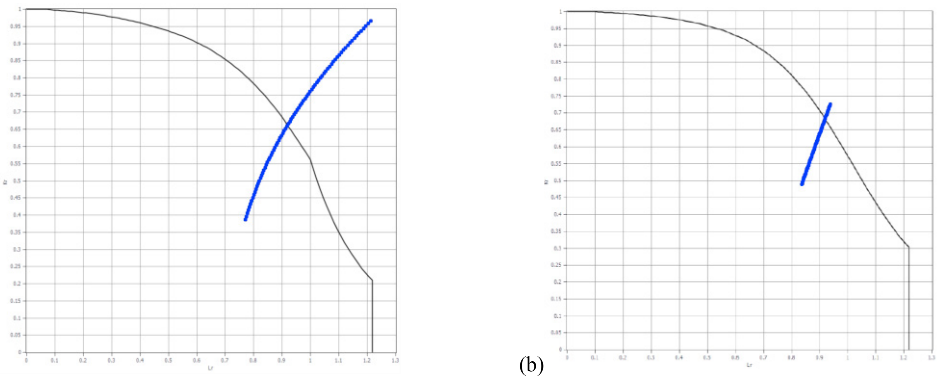
(a) (b)

Fig. 6. FP-TTF-5 (a) and FP-EF-3 (b) determination of the flaw critic length

Considering the importance of the matter, a detail analysis was done for the presented flaws. The procedure uses FAD-2 assessment data, and it gives the critical dimension of the crack.

The input data are the same as for FAD-2 assessment.

The results are presented in table 4 and for FP-TTF-5 and FP-EF-3are presented graphically in figure 6 (a) and Figure 6 (b).

Table 4. FAD 2 – critical dimension of the flaw (with corresponding figures and flaw name – figure 6.17 and table 6.4)

Case no.	Case name	B	W	$2a_0$	a_0	$2c_0$	p_0	r_0	h_0	t_w	Flaw Critic Height	Flaw Critic Length
		mm	*mm*	*mm*	*mm*	*mm*	*mm*	*mm*	*mm*	*mm*	*mm*	*mm*
1	FP-TTF-1	16	200	30							N/A	36.249
2	FP-TTF-2	32.63	200	30							N/A	36.249
3	FP-TTF-3	200	32.63	10							N/A	11.330
4	FP-TTF-4	25	200	30							N/A	36.243
5	FP-TTF-5	25	120	30							N/A	28.408
6	FP-EF-1	16	200		15						N/A	17.230
7	FP-EF-2	32.63	200		15						N/A	17.230
8	FP-EF-3	200	32.63		5						N/A	7.507
9	FP-EF-4	25	200		15						N/A	17.230
10	FP-EF-5	25	120		15						N/A	14.750

5. Conclusions

There were assessed several types of flaws that can be meet in a steel shell structure. Different types of locations were taken into account thus resulting groups of flaws which were assessed and compared – from in the plate flaw (e.g. flange plate joint near the welded joint), to the edge flaw in the area of the flange (e.g. nearby a bolt hole).

The input data took into account the results from the FEM analysis of structure and the experimental results for material properties, all needed in the assessment procedures.

The comparison of the flaws assessment with fracture mechanics procedures, revealed several problems:

- Sensibility of the joints to the through thickness flaw in the endplate of the segment joint (FP-TTF-5). In case of a only 30mm flaw, the element fails;
- The edge flaw type – FP-EF-3 (flaw in the fillet welding of the shell element and the endplate – segment joint), is the most dangerous – a 15mm crack depth into welded joint is a critical flaw for which the joint fails.

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