Steel antenna towers – from designing to manufacturing optimization

D Radu1* and A Feier2

1 Faculty of Civil Engineering, Transilvania University of Brașov, 500152, 5 Turnului St., Brașov, Romania
2 Department of Materials and Manufacturing Engineering, Politehnica University of Timișoara, Timișoara, Romania

*E-mail: dorin.radu@unitbv.ro

Abstract. The 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). An Engineering Critical Assessment 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. The paper presents some considerations on the designing and manufacturing process, taking into account structural assessment procedures using fracture mechanics. It also presents a study case – a steel monopole tower on which the method is applied, in order to assessing the possible discovered flaws in the designing phase. Ten types of flaws which can be discovered in the service time of the structure were assessed. Different types of locations were taken into account, thus resulting groups of flaws which were then assessed and compared.

1. Introduction
Due to the rapid growth of the telecommunication industry, the development of relevant infrastructure has been gaining importance. Modern telecommunication structures are essential to the present society. The emergence of new technologies creates a demand for additional facilities and for the introduction of new elements into our cities.

In fast developing countries, faced with high density of population in urban areas, great difficulties are experienced in finding land for the setting up of conventional lattice towers for communication purposes. A serious increase in land value has called for a suitable alternative to conventional lattice towers that should be friendly and unobtrusive to the environment. Environmental and economic pressures have require improved design approaches to make communication towers more environmentally acceptable and cost effective. Steel pole structures are used in different fields such as power transmission, communication, high way and stadium illumination. Steel tubular poles have a smaller plan dimension and are composed of fewer components compared to the lattice type towers.

When these poles are used as antennae supporting structures, they are more economical as far as the cost of land is concerned. These poles are either slip jointed or connected using bolted flange
plates. The pole weight affects the overall cost of the system consisting of the overall cost of the material, manufacturing, transportation and erection. Following the need of upgrading to high standards of signal transmission, in Romania and not only, the telecommunication network is rapidly growing. There is an undeniable need for the design and erection of communication towers.

The aim of the present paper is to apply fracture mechanics in the assessment of the in structure possible discovered flaws. The assessment procedure, called ECA - Engineering Critical Assessment, can be applied starting with the design process, to elements’ manufacturing or in service. As a study case, the paper presents a steel monopole tower structure to which the assessment of the possible flaws in the design phase is applied.

2. Engineering critical assessment approach
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 [1], or 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 concept (also termed 'fitness-for-purpose analysis') is widely accepted by a range of engineering industries; however, in civil engineering it is not used very often.

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. These information can be obtained partly as a result of a structural analysis made by a civil engineer, and partly by a materials testing and fracture mechanics analysis performed by a mechanical engineer.

The analysis is carried out in accordance with the British Standard procedure BS 7910 ('Guide to methods for assessing the acceptability of flaws in metallic structures') [2]. 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 [3].

For design purposes, or for the 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. 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.

Considering the FM approach for a specific steel structure with welded joints, the with flaw elements can be divided into:

- safe in which the flaw/flaws will not grow to a critical size during the service life,
- safe if regularly inspected, the flaw/flaws is/are on the borderline of reaching a critical flaw size during the service life, and regular inspection is therefore necessary,
- repair is mandatory – the flaw/flaws is/are already so critical that there is every possibility of failure and they thus exceed the permissible risk in terms of safety.

ECA is characterized by applying FM in assessing specific flaws for steel elements joints, fatigue assessment of the steel elements with typical flaws, remaining lifetime calculation for steel structures containing flaws / cracks, determining the inspection interval for steel structures – risk analysis for different flaws [2, 4].
3. Case study – ECA applied for an antenna tower
The study is carried out following the need of the investor to assess the reliability in time of a number of 15 antenna towers. Given the number of sites, the ECA needed to be applied from the designing phase – for a given future discovered flaw to evaluate the implications in the behaviour of the structure.

The column is a 30 m height monopole type CHS profile (610 mm in diameter) column and it presents three segments – two segments of 12.00 m and one segment of 6.00 m. At the upper side (4.00 m from the top) a technical maintenance platform will be attached, as well as four antennas (with a total wind exposure area of 0.79 m²) (figure 1).

Figure 1. Geometry of the antenna tower – general views.

3.1. Loads evaluation and analysis methods
In order to apply the ECA from the design phase, four phases needed to be covered:
- loads evaluation with an in depth wind load assessment,
- global numerical analysis – linear elastic analysis,
- determining the critical stress in the given flaw,
- flaw geometry (assessment for a given flaw),
- material fracture toughness determination,
- applying failure assessment diagrams (level 1 and/or level 2) for a given flaw.

Regarding the wind, it was evaluated according to the Romanian normative CR1-1-4 [5], considering the structure in the area of \( q_p = 0.6 \) kPa with the terrain category II. From the dynamic analysis what resulted was a frequency of the structure of 0.42 Hz, with coefficient \( c_{s,c,d} = 0.984 \). The wind on the tower was evaluated on the surface of the cylinder and on the top of the structure – onto the antennas. The total value of the wind load onto the antenna area was calculated \( F_{w_{tot}} = 22.11 \) kN according to [5]:

\[
F_w = \gamma_{cf} \cdot c_d \cdot c_f \cdot q_p(z_e) \cdot A_{ref}
\]  

Following the linear analysis, a maximal stress of 311.12 \( \text{N/mm}^2 \) was determined, and it was identified in the area of the baseplate of the monopole. In order to assess a given flaw in a given area, multiple cases were detailed (table 1). An in-depth analysis (FEM type) was required in order to
evaluate the flaws in the joints. With Abaqus software [6], several analyses were ran, thus determining the stresses in the flaw risk areas (figure 2).

![Figure 2. Equivalent stress values in the area of the (a) base plate joint; (b) segment joint.](image)

Given the number of produced assemblies, the material fracture properties were determined prior to manufacture [7]. The experiments were conducted on the base material, thus the values of fracture mechanics properties were valid for the designed and future manufacture structure. The value of 78.92 MPa m$^{1/2}$ was determined on the specimens. This value will be used in further assessments.

**Table 1. FEM analysis results - stresses in the flaw risk areas.**

| Flaw risk area                                      | FEM analysis result (MPa) | Attached given flaw |
|-----------------------------------------------------|---------------------------|--------------------|
| Base plate - foundation connection                   | 312.55                    | FP-TTF, FP-SF, FP-BF |
| Segment joint 1 (level of 12m)                       | 202.45                    | FP-TTF, FP-SF, FP-BF, FP-EF |
| Segment joint 2 (level of 24m)                       | 182.16                    | FP-TTF, FP-SF, FP-BF, FP-EF |

A taxonomy was made of the flaws in order to have a complete behaviour view of the design structure with a clear description of each flaw (table 2).

**Table 2. Description of each flaw.**

| Name   | Flaw type                      | Description of the flaw                                                      |
|--------|--------------------------------|-------------------------------------------------------------------------------|
| FP-TTF | Flat plate - through thickness flaw | Crack in the column base or in the segment endplate joint                   |
| FP-SF  | Flat plate – surface flaw       | Crack in the base material (tube wall)                                       |
| FP-BF  | Flat plate – buried flaw        | Crack in the base material (tube wall)                                       |
| FP-EF  | Flat plate – edge flaw          | Crack in the flange of the segment joint or column base in proximity of the welding longitudinal or transversal direction |
3.2. Applying Failure Assessment Diagrams

The Failure Assessment Diagram (FAD) describes the interaction between the brittle fracture and plastic failure through the $F_r = f(S_r)$ 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. Thus, the fracture mechanics assessment is crucial. The special circumstances that would be called into play in the upper right corner of figure 3 in this regime, a cracked structure would experience large-scale plastic deformation prior to crack extension [1].

![Failure Assessment Diagram](image)

**Figure 3.** 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 [8]

The level 2 (FAD-2) assessment is the normal evaluation path for general application. The method presents 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 on the outside area, the flaw is considered unacceptable [9].

The equations describing the assessment line are:

$$\sqrt{\delta_r} \quad \text{or} \quad K_r = \left( t - 0.14 L_r^2 \left[ 0.30 + 0.70 \exp(-0.65 L_r^6) \right] \right) \quad \text{for} \quad L_r \leq L_{r\text{max}}$$

(2)

$$\sqrt{\delta_r} \quad \text{or} \quad K_r = 0 \quad \text{for} \quad L_r > L_{r\text{max}}$$

(3)

The cut-of line is fixed in point where $L_r = L_{r\text{max}}$, where:

$$L_{r\text{max}} = \frac{\sigma_Y}{\sigma_u} = \frac{(\sigma_Y + \sigma_u)}{(2\sigma_Y)}$$

(4)

in which:

- $\sigma_Y$ – the yielding resistance of the material
- $\sigma_u$ – the ultimate resistance of the material

For the assessment on level 2, a FAD is necessary to pass through the following phases [6]:

- determining the stresses – following a structural analysis. The assessments consider the real distribution of stresses in the proximity of the flaws – $P_m$, $P_b$, $Q_m$ and $Q_b$.
- the fracture ratio $K_r$ must be determined

$$K_r = \frac{K_I}{K_{mat}}$$

(5)

in which $K_{mat}$ represents the fracture toughness of the assessed material, determined at the service temperature.
The stress intensity factor (SIF) – \( K_I \) is determined with the following relation:

\[
K_I = (Y \cdot \sigma)(\pi a)^{1/2}
\]  

(6)

where

\[
Y \cdot \sigma = (Y \cdot \sigma)_P + (Y \cdot \sigma)_S
\]  

(7)

in which:

- \((Y \cdot \sigma)_P\) – contribution of the main stresses
- \((Y \cdot \sigma)_S\) – contribution of the secondary stresses

\[
(Y \cdot \sigma)_P = M \cdot f \cdot w \cdot \{k_{tm} \cdot M_{km} \cdot P_m + k_{th} \cdot M_{th} \cdot M_b \cdot \{P_b + (k_{mb} - 1) P_m\}
\]  

(8)

\[
(Y \cdot \sigma)_S = M_{km} \cdot Q_m + M_{th} \cdot Q_b
\]  

(9)

- Determining the ratio of stress \( L_r \) according with:

\[
L_r = \frac{\sigma_{ref}}{\sigma_Y}
\]  

(10)

in which \( \sigma_{ref} \) is obtained according with a relation specific with the flaw type. The points/points of assessment are represented graphically in \((K_r, L_r)\) coordinates on the FAD level 2 [6].

- The evaluation of the position of the point is made according with the specifications.

For the in case structure assessment level 2 – FAD-2, assessments were made on different flaw types and flaw positions. The values of the input data are:

- \( \sigma_Y \) (yield strength) = 355 MPa; \( \sigma_T \) (ultimate strength) = 510 MPa; S355J2 steel type,
- \( K_{mat} = 78.92 \text{ MPa} \cdot \text{m}^{1/2} \) was determined on the specimens (through testing),
- \( P_m \) = primary stress according to table 1 and table 2 (determined following a structural analysis),
- \( k_{tm} = 1; k_{th} = 1 \) (stress concentrators factors),
- \( Q_{km} = 0 \) (thermal membrane stress) and \( Q_{th} = 0 \) (thermal bending stress),
- \( Q_{km} = 0 \) (residual membrane stress) and \( Q_{th} = 0 \) (residual bending stress).

3.3. Results

Considering the position of the flaw regarding the stress direction and position in the assembly of the steel shell element, 10 types of assessed flaws resulted, as presented in table 3. In figure 4 there is graphically presented the assessment results for the FP-TTF group.

**Table 3.** Results on the assessed flaws

| Case   | B (mm) | W (mm) | a (mm) | 2c (mm) | p (mm) | r₀ (mm) | h (mm) | t₀ (mm) | L_r | K_r |
|--------|--------|--------|--------|---------|--------|---------|--------|---------|-----|-----|
| 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-SF-1   | 25     | 200    | 30     |         |        |         |        |         | 0.8318 | 0.6755 |
| FP-SF-1   | 25     | 120    | 30     |         |        |         |        |         | 0.9427 | 0.6930 |
| FP-SF-3   | 16     | 200    |        |         |        |         |        |         | 0.7644 | 0.7688 |
| FP-EF-1   | 32.63  | 200    | 15     |         |        |         |        |         | 0.7644 | 0.7688 |
| FP-EF-2   | 200    | 32.63  | 15     |         |        |         |        |         | 1.3086 | 1.6678 |
| FP-EF-3   | 25     | 200    | 15     |         |        |         |        |         | 0.7644 | 0.7688 |
| FP-BF-1   | 16     | 200    | 5      | 30      | 3      | 7       |         |         | 0.8080 | 0.8139 |

4. Conclusions

The engineering critical assessment procedure was applied from the design phase. Ten types of flaws which can be discovered in the service time of the structure were assessed. Different types of locations were taken into account, thus resulting groups of flaws which were assessed and compared.
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-3 - crack in the column base or in the segment endplate joint) [10];
- the edge flaw type – FP-EF-2 (Crack in the flange of the segment joint or column base in proximity of the welding longitudinal or transversal direction), is the most dangerous – $a = 15$ mm crack depth into welded joint is a critical flaw for which the joint is considered unsafe [11].

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

References
[1] Radu D and Gălățanu T 2017 Fracture mechanics critical assessment of the steel structures joints Conference proceedings - 5th International Conference Contemporary Achievements in Civil Engineering pp. 261-269
[2] ***, BS 7910/2013, “Guide to methods for assessing the acceptability of flaws in metallic structures”, BSI British Standards
[3] Radu D, Sedmak A, Sedmak S and Dunjić M 2018 Stress analysis of a steel structure comprising cylindrical shell with billboard tower Technical Gazette 25 no.2/2018 pp. 212-217
[4] Milović Lj and Sedmak A 2007 Numerical and analytical modeling of elastic-plastic fracture mechanics parameters Materials Science Forum 555 pp. 565-570
[5] ***, CR1-1-4/20012 - “Cod de proiectare. Evaluarea actiunii vântului asupra constructiilor”
[6] ***, Abaqus software guide.
[7] Sedmak S and Sedmak A 2009 Fracture mechanics and non-destructive testing for structural integrity assessment Key Engineering Materials 399 pp. 27-36
[8] Kanninen M F and Popelar C H 1985 Advanced Fracture Mechanics Oxford University Press
[9] Petzek E 2006 Elaborarea de instructiuni pentru aplicarea principiilor mecanicii ruperii la stabilirea siguranței în exploatare și a duratei de viata rămase a podurilor metalice existente Orizonturi Universitare Publishing house, Timișoara
[10] Rakin M, Gubeljak N, Dobrojević M and Sedmak A 2008 Modelling of ductile fracture initiation in strength mismatched welded joint *Engineering Fracture Mechanics*. 75 (11) pp. 3499-3510

[11] Radu D, Sedmak A, Gălățanu T and Taus D 2017 Fracture Mechanics applied on investigation of the existing lattice structures *International Scientific Conference CiBV 2017 - Bulletin of the Transilvania University of Brașov* 10 (59)