Damage Accumulation-based and FEA-aided Fatigue Life Evaluation of Tubular Structures

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Abstract

Fatigue assessment of tubular structures in various applications according current design codes is based on S-N criteria with uncertain characterization of the damage. In case the crack is detected residual service life may be estimated by applying the Linear fracture mechanics techniques, again, with incomplete defining the exhaustion of life. An approximate procedure based on application of the Strain-life criterion for fatigue failure and of the finite element modeling of successive damage accumulation is implemented for evaluation of fatigue life of tubular components under the cyclic loading. The procedure allows assessment of fatigue life from the moment structure is put into service up to the through crack development in the shell, or alternatively, up to the onset of fast fracture conditions. Efficiency of the approach is illustrated in example of fatigue life evaluation of the pipeline component subjected to internal pulsating pressure.

1 Introduction

The current rules for fatigue design of structures are based on application of the S-N (Stress-Life) approaches which presume assumption that material of a structure deforms elastically in service loading conditions. The mechanics of fatigue damage of a material is implied (not definitely specified) as built into the design S-N curves based on analysis of results of fatigue testing of the base material and typified welded joints (e.g., [1]). Specific of the testing procedure is the termination of test when initiated and growing fatigue crack notably affects the specimen compliance preceding complete fracture. Respectively, when the test data are applied to assessment of fatigue resistance of a structural detail, the state of damage, corresponding crack size occurs uncertain.
When in the service conditions fatigue crack is detected the residual fatigue life of a structure is recommended to estimate by using the Linear fracture mechanics approach, i.e. by evaluation of the stress intensity factor values through the anticipated crack progress in affected component and further by integrating the Paris equation. However, the stress intensities may be calculated only if the stress field at the crack tip (or the crack front) is characterized by singularity. When the crack initiated, e.g., in a tubular component or in a pipe shell, would approach the back face of

the shell, the stress field in ligament becomes non-singular, at relative depth of the crack, approximately, 0.7-0.8 of the shell thickness [2]. Consequently, the through crack regarded as indicator of the limit state of a component can not be assessed.

An attempt was made to apply the strain energy approach in conjunction with the Hutchinson-Rosengren stress-strain field solution for the near crack tip area to predict crack growth considering for the material plasticity [3]; again, the problem of incorporating the crack initiation stage into the continuous fatigue process was not solved.

Summing up, it may be stated that the fatigue life evaluation presently is composed of application of the two approaches, but the link between these is missing and the limit state may be estimated in the course of the fatigue crack extensions only when the conditions for fast fracture are attained.

A reasonable solution of the fatigue life problem may be application of the approach based on implementation of the Strain-life criterion and the damage accumulation in material elements supported by the means of the finite-element modeling of the crack initiation and growth.

2 Description of the approach

The Strain-Life approach considered in the present rules as optional may be a reasonable method for fatigue analysis and design of structures by the mentioned reasons. The approach includes an appropriate Strain-Life criterion for fatigue failure of material together with the experimentally obtained lumped stress-strain cyclic diagram. The damage accumulation procedure developed for fatigue assessment under irregular loading in crack analysis is necessarily supported by the finite-element modeling of the affected structure.

According to the approach the expected crack path is considered in design of the finite element mesh, the finite elements assumed the grain clusters with approximately close (or, alternatively, random) slip resistance. The damage is supposed to be uniformly distributed within these elements. Each element is provided with a scalar damage variable, estimated by the selected damage accumulation theory for irregular loading. The number of cycles prior to failure of each element is evaluated using the Strain-life Manson's criterion.

When the damage in the element reaches a critical unity, its compliance is artificially increased, and nodal forces are redistributed in the surrounding elements. The damage calculation is repeated considering for the renewing stress-strain state ahead the crack tip; "killed" elements form the crack front progress.

This idea was first suggested in pioneering studies of G. Glinka and F. Ellyin focused on analysis of cracks in thin plates at the plane stress [4, 5]; further analysis had shown that the procedure may be applied to assessment of fatigue process including crack initiation and growth of plane cracks in arbitrary bodies [6, 7].

3 Fatigue life assessment of a pipeline loaded by the inside pulsating pressure

The briefly explained in above approach is applied for fatigue life evaluation of a pipeline subjected to pulsating pressure from inside. The fatigue life is estimated as initiated in undamaged structure from the very first load application until development of the through crack.

Fig.1 shows failure of a pipeline along the generating line caused by hoop stress. Respectively and accordingly the principles of modeling fatigue process the finite element model of the cylindrical shell is designed where the fatigue crack initiation and growth may be expected. The size of elements is assumed encircling a number of grains characterized by approximately equal resistance to the cyclic loading. The finite-element model of a fragment of the pipeline is presented in Fig.2. The arrow shows the fine mesh at the expected fatigue crack origination and propagation through the shell thickness.

Figure 1: Example of the through crack in a fractured pipeline

Material of the pipeline - higher strength steel 09G2 grade, the yield stress of which $\sigma_y = 300$ MPa, ultimate strength $\sigma_u = 450$ MPa. Resistance of the material (finite elements) to cyclic loading is characterized by the strain-life (Manson's) criterion [8], parameters of which are given in [9]:

$$\Delta\varepsilon = \Delta\varepsilon_p + \Delta\varepsilon_e = CN^{-\alpha} + BN^{-\beta}, \tag{1}$$

where $\Delta\varepsilon_p$ is the plastic strain range component, $\Delta\varepsilon_e$ is the elastic strain, $C = 0.34$ (the crack is expected in rolling direction of the plate steel, Bкlamellar-tearingBњ effect considered), $B = 0.011$, $\alpha = 0.654$, $\beta = 0.170$.

The stabilized lumped cyclic curve of the steel obtained based on the principle of equivalent strain energy also taken from [9] is given in Table 1.

To initiate the fatigue process in selected area (fine mesh area) several elements at the inner surface of the shell are provided with reduced cyclic proportionality stress with respect to that for elements of the model.

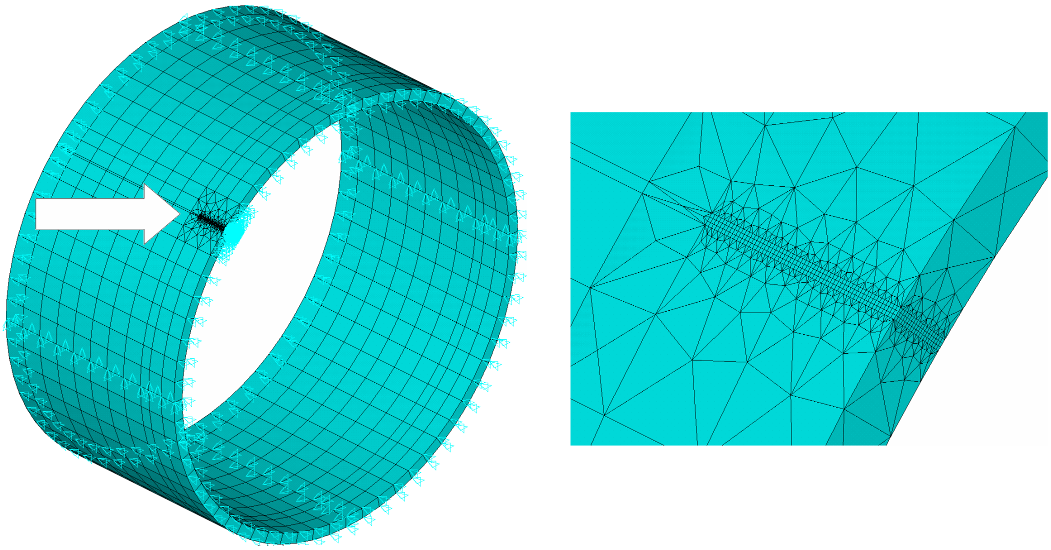

Figure 2: FE model of the pipeline and fragment of the shell (right-hand) with fine mesh where the crack is expected

Table 10: Stabilized lumped cyclic curve of the 09G2 grade steel

$\Delta\sigma$, MPa	105.0	210.0	303.2	363.2	435.0	482.1
$\Delta\varepsilon$	0.0005	0.0010	0.0015	0.0020	0.0025	0.0030
$\Delta\varepsilon\Delta\sigma$	0.0525	0.2100	0.4548	0.7264	1.0875	1.4463

With initiation of cyclic loading the damage accumulation in elements is estimated by applying the Palmgren-Miner linear damage summation rule. In initial step of the procedure, $j = 1$, the strain field in "i" elements located in the area of expected crack extensions is calculated. The number of cycles to failure of the above mentioned "weak", the most affected, elements is estimated by the criterion (1). The damage in initial step is calculated also for the elements of surrounding volume; the damage for failing elements is equal to unity. Failure of elements is modeled by decreasing the stiffness of those by several decimal orders with respect to the stiffness of surrounding volume of material. Through the following step the new stress-strain field (changed in the course of failure of elements forming the crack extensions) in elements is calculated and failure of sequential elements is assessed considering the damage accumulated at the previous steps.
So far, the damage accumulated in i-th element through "j" steps can be presented in the form of the recurrence:

$$d_i^j = \sum_j min\{n_i^j\}/N_i^j = \sum_j min\{N_i^j(1 - d_i^{j-1})\}/N_i^j, \tag{2}$$

where n_i^j is the number of cycles prior to failure of i-th element at the j-th step. The total accumulated damage at every sequential step of the procedure depends on the previous damage magnitude and on failure of elements in the affected area. For every element the number of step, j_{cr}, when it fails, may be indicated; the minimum number of cycles prior to failure at this step is related to this particular i-th element:

$$min\{N_i^{j_{cr}}(1-d_i^{j_{cr}-1})\} = N_i^{j_{cr}}(1-d_i^{j_{cr}-1}). \tag{3}$$

Respectively, the damage in i-th element corresponding to failure may be presented as:

$$d_i^{j_{cr}} = d_i^{j_{cr}-1} + min\{n_i^{j_{cr}}\}/N_i^{j_{cr}} = d_i^{j_{cr}-1} + N_i^{j_{cr}}(1-d_i^{j_{cr}-1})\}/N_i^{j_{cr}} = 1. \tag{4}$$

When the crack initiates the problem of effective part of the load cycle arises which concerns the phase when the crack opens and up the maximum load. The crack opening effect can be taken into account within this approach by introducing an effective strain range in the failure criterion via total strain range multiplied by the crack opening parameter identical to that suggested by Elber [10]:

$$\Delta\varepsilon_{eff} = U\Delta\varepsilon. \tag{5}$$

It was shown [6] that crack opening parameter, U, can be estimated by changing the stress sign in elements at the crack tip in direction perpendicular to the crack front.
The procedure was applied to calculate both the crack expansion and number of cycles in several steps. Fig. 3 illustrates the crack progress initiated at the inner surface of the shell until it reaches the outer surface and becomes the through-crack. The crack front seems a relatively short along the cylindrical shell generating line. This may be explained by relatively short model of the affected area where the mesh is essentially fine (with respect to the shell thickness), Fig.2.
The fatigue life of the pipeline assessed from the initiation of cyclic loading up to the through crack is illustrated in Fig.4 as the dependence of the number of cycles on the hoop stress range.

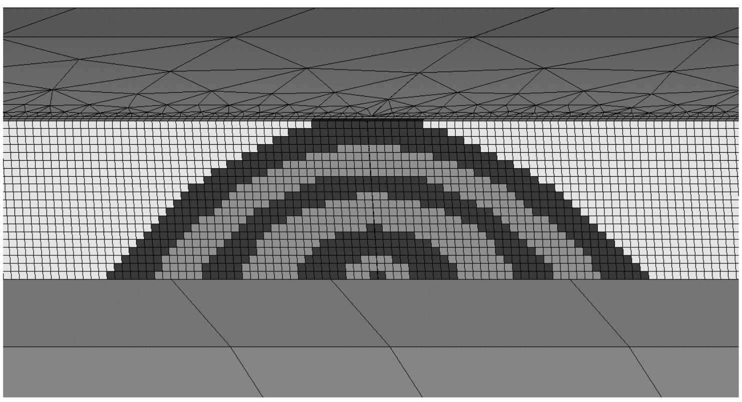

Figure 3: Crack progress towards the outer surface of the pipeline

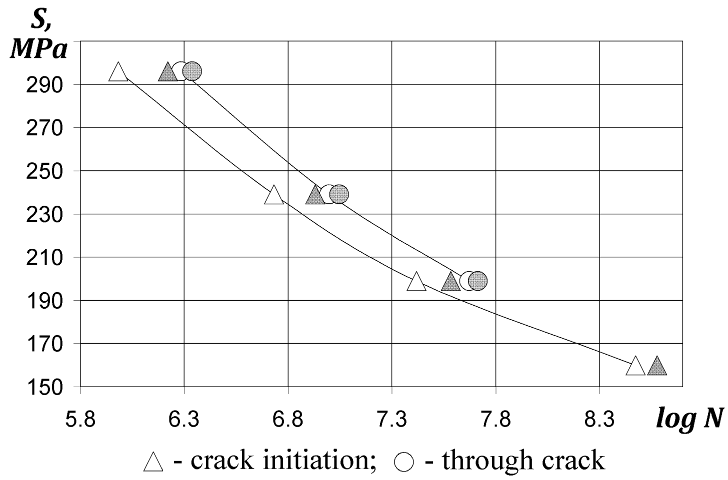

Figure 4: Fatigue life of the pipeline

4 Conclusions

The approach based on application of the Strain-life criterion for fatigue, characterization of the cyclic elastic-plastic properties of material (cyclic stress-strain curve), damage summation procedure and finite-element modeling of structure with the due attention to FE-modeling of the critical area provides evaluation of fatigue life of a structural component including both, the crack initiation and the crack propagation phases. In considered example of the pipeline, it is shown that the fatigue can be assessed from the initiation of cyclic loading (pulsating pressure of the transported media in pipeline) up to formation of the through crack.

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