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FATIGUE LIFE EVALUATION OF RION - ANTIRION CABLE-STAYED BRIDGE USING THE MULTISCALING FRACTURE MECHANICS APPROACH

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ABSTRACT: Innately fatigue failure is a typical problem between two different scales because fatigue crack growth increases from microscale to macroscale. Classical continuum mechanics is inadequate to deal with such a problem, since it disqualifies the effect of the scale, making the assumption that the material is continuous and homogeneous, something that is not applicable in microscale due to the discontinuity and inhomogeneity of materials. In this paper is made an effort to fill the gap between microscale and macroscale in the process of continuous fatigue of suspension and cable-stayed bridges cables. This problem is solved according to the application of the mesoscopic fracture mechanics theories. To illustrate the proposed approach the Charilaos Trikoupis Bridge (Rion - Antirion Bridge) has been chosen to perform the numerical computations. From the numerical computations results it can be concluded that the size of the initial crack is the primary factor for the life expectancy of steel wires. Consequently the life expectancy of the suspension and cable-stayed bridges cables depends on the size of the initial crack too.

KEY WORDS: Cable stayed bridge; Mesoscopic fracture mechanics; Micro / Macro dual scale crack; Multiscale; Fatigue life.

1 INTRODUCTION

The reduction of the life expectancy of steel wires depends on many factors as cracking due to mechanical stress, corrosion, hydrogen embrittlement and fatigue. These factors endanger strength and wire ductility. Therefore the accurate estimate of life expectancy due to steel wire fatigue is necessary for the safety of the bridge [1]. The life expectancy of steel wires is estimated from statistic research using fatigue results [2].

Nevertheless, the fatigue problem has not a complete solution and is still in the process of research despite that it is an old problem. In conclusion, the fatigue process is divided into two stages, the first stage is fatigue crack initiation and the second stage is the fatigue crack propagation. The aforementioned derive from different theories and are dealt with individually [3],[4].

In recent years it has been formulated a theory called multiscaling crack models theory [5]. To describe a crack from microscale to macroscale there has been proposed a dual scale crack using the factor of stress intensity or energy density. In this paper a multiscale crack model is used that takes into account the different scales. The results of this research will be able develop control processes for the betterment of the Rion - Antirion Bridge safety

2 GENERAL

2.1 Physical model

The multiscale crack model is based on the assumption of the appearance of restraining zone stress, as shown in *Fig.1*. In *Fig.1(*a*)* is shown a plate under uniaxial tension without damage. Supposedly that exists one crack in the center of the plate as shown in *Fig.1(b)* the stresses will appear in the edge of the crack that are indicated as σ_0. If the ratio of restraining stress to applied stress, $\sigma_0/\sigma\infty$, then $\sigma_0 = \sigma\infty$ case a and b is the same. If $\sigma_0=0$, then case b and c are identical, *Fig.1(c)*.

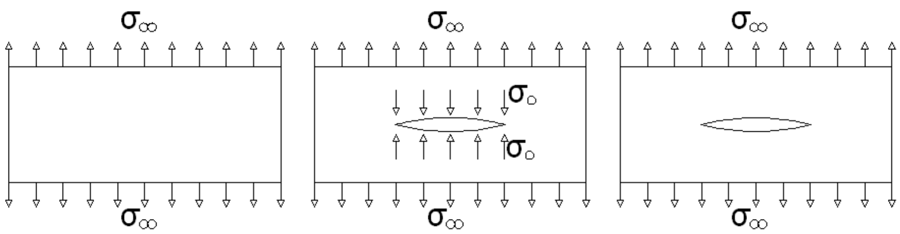


Figure 1. Crack micro to macro scale

According to the multiscale crack model, the restraining zone stress can define the fatigue process with continuous way. This way the fatigue process is analyzed in an integrated theory and the separation of the fatigue process into two stages is not needed [6]. The macro/micro dual scale energy density factor range Δ^{macro}_{micro} micro in a fatigue process for the dual scale edge crack model can be written as :

$$\Delta^{macro}_{micro} = \frac{2(1-2\nu_{micro})(1-2\nu_{macro})^2\sigma_a\sigma_m}{\mu_{macro}}\mu^*(1-\sigma^*)\sqrt{d^*}\sqrt{\frac{d_0}{r}} \qquad (1)$$

where :

$$\mu^* = \frac{\mu_{micro}}{\mu_{macro}}, \ \sigma^* = \frac{\sigma_0}{\sigma_\infty}, \ d^* = \frac{d}{d_0} \tag{2}$$

$$\sigma_a = \frac{\sigma_{max} - \sigma_{min}}{2}, \ \sigma_a = \frac{\sigma_{max} + \sigma_{min}}{2} \tag{3}$$

The ν_{micro} and ν_{macro} are the microscopic and macroscopic Poisson's ratio respectively, σ_{max} and σ_{min} are the maximum and minimum stress respectively, μ_{micro} and μ_{macro} are the microscopic and macroscopic shear module respectively and σ_0 and σ_∞ are the restraining stress and applied stress respectively. Also, d_0 is the crystalline grain size and r is related to the crack segment length at each time.

2.2 Fatigue crack growth

The crack growth ratio dα/dN from microscale to macroscale in cables Δ_{micro}^{macro} depends on the dual scale energy density factor. According to the dual scale crack model the crack growth ratio can be expressed as:

$$\frac{da}{dN} = C_0 (\Delta S_{micro}^{macro})^n \tag{4}$$

where : C_0 and n are material fatigue parameters

For the high strength steel wire Eq.(4) is simplified to

$$\frac{da}{dN} = C_0 (\Delta S_{micro}^{macro}) \tag{5}$$

Inserting Eq(5) into Eq(1) yields:

$$\frac{da}{dN} = C_0 \frac{2(1-2\nu_{micro})(1-2\nu_{macro})^2 a \sigma_a \sigma_m}{\mu_{macro}} \mu^* (1-\sigma^*) \sqrt{d^*} \sqrt{\frac{d_0}{r}} \tag{6}$$

By defining a parameter C as

$$C = C_0 \frac{2(1-2\nu_{micro})(1-2\nu_{macro})^2}{\mu_{macro}} \tag{7}$$

Eq.(6) then becomes

$$\frac{da}{dN} = C a \sigma_a \sigma_m \mu^* (1-\sigma^*) \sqrt{d^*} \sqrt{\frac{d_0}{r}} \tag{8}$$

By the numerical integral operation from Eq.(8)

$$\Delta\alpha_i = Ca_{i-1}\sigma_a\sigma_m\mu^*_{(a_{i-1})}(1-\sigma^*_{(a_{i-1})})^2\sqrt{d^*_{(a_{i-1})}}\sqrt{\frac{d_0}{r}}\Delta N \tag{9}$$

$$\text{and } \alpha_i = a_{i-1} + \Delta\alpha_i \tag{10}$$

3 THE RION – ANTIRION BRIDGE

3.1 Geometrical and technical data

Photo 1. Rion - Antirion bridge

The Charilaos Trikoupis Bridge (Rion - Antirion Bridge), is the world's longest multi-span cable-stayed bridge that is 2252 m long. It crosses the Gulf of Corinth near Patras, linking the town of Rio on the Peloponnese to Antirrio on mainland Greece by road. The bridge deck is suspended with 368 cables from 4 pylons. According to the aforementioned there are 46 pairs of cables which are fixed to every pylon bilaterally [7]. The 4 pylons divide the bridge into 5 spans with the following: 286m-560m-560m-560m-286m the geometry of which is shown in *Fig.2* [8].

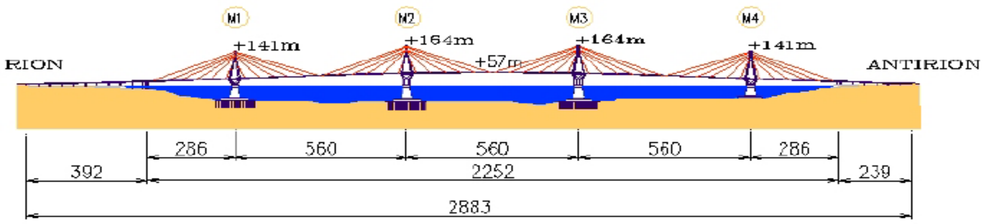


Figure 2. Rion - Antirion dimensions

Every cable constitutes of 43 – 73 clones wrapped in PVC. The classification of the number of clones in every cable is done with the purpose that the mean stress is equal in every cable. Every clone has diameter 15.7 mm and consists of

7 parallel wires. The effective area of every clone is 150 mm^2 and the ultimate tension stress strength of the wires is 1770 MPa [9].

3.2 Loads

The loads for which the bridge is calculated are:

- Dead Loads
- Live Loads (according to EC-1)

3.3 Modeling of bridge

The modeling of the bridge is accomplished with the use of software that specializes in linear elastic analysis with the finite element method. The model was designed on the basis of the geometry, the mechanical parameters of the materials and the statical function of each element and is constituted of:

- **Beam elements**: Linear elements with 6 d.o.f. per joint.
- **Pylon elements**: Linear elements with 6 d.o.f. per joint.
- **Cable elements:** Linear elements with compression release.
- **Brace elements:** Linear elements with 3 d.o.f. per joint.
- **Plate elements:** Shell finite elements with 5 d.o.f. per joint

4 RESULTS

4.1 Stress analysis in steel wires

- Cable force due to dead loads: Ng=6732kN
- Cable force due to live loads: Nq=1641kN

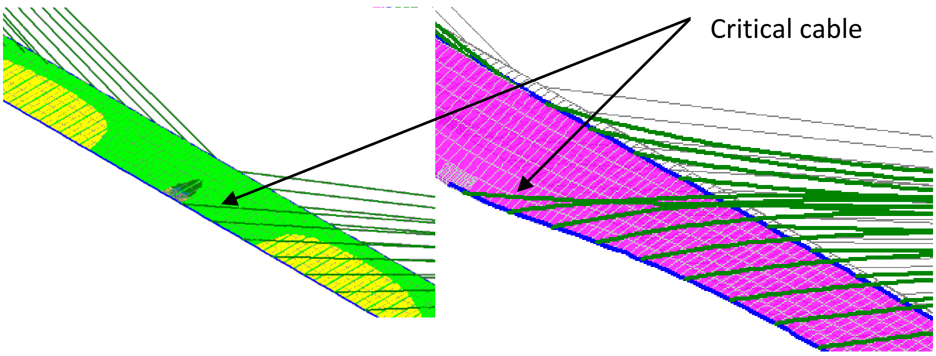


Figure 3. Critical cable

However, the stress distribution in the cable section is not uniform in fact. This indicates that the stress value of each wire in the same cable must be different. In addition, the cable forces would vary with time due to the tightening and loosening effects caused by many reasons. According to the aforementioned two parameters A and B are inserted in Eq.(3) which yields:

$$CaseI: \ \sigma_a = \frac{A\sigma_{\max} - \sigma_{\min}}{2}, \ \ \sigma_m = \frac{A\sigma_{\max} + \sigma_{\min}}{2} \tag{11}$$

$$CaseII: \ \sigma_a = \frac{\sigma_{\max} - B\sigma_{\min}}{2}, \ \ \sigma_m = \frac{\sigma_{\max} + B\sigma_{\min}}{2} \tag{12}$$

The factors A and B take into consideration the tightening and loosening factors only live loads or only dead loads accordingly

4.2 Critical dimensions of the crack

For the determination of the critical crack depth is using the macroscopic fracture mechanic theory. The fracture toughness K_{Ic}, of the steel [9] is:

$$K_{Ic} = 50.00 \text{ MPa.}\sqrt{\text{m}}$$

For define the stress intensity factor is using a semi-elliptical surface crack in a long shaft under tension theory as shown in *Fig.4* [10].

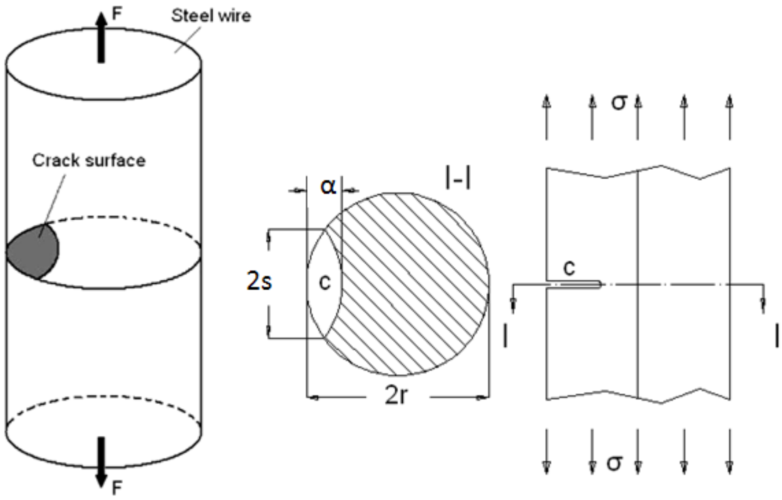


Figure 4. Semi-elliptical surface crack in a long shaft under tension

The stress intensity factor (SIF) at the deepest point c of a semi-elliptical crack front is:

$$K_I = F_I \ \sigma \ \sqrt{\pi\alpha} \tag{13}$$

where the factor F_1 is calculated from *table* 1.

Table 1. Values of F_I

α/r	0	0.125	0.250	0.375	0.500
F_I(α/s=0.5)	0.884	0.890	0.920	0.976	1.064

From application the simple criterion K_I=K_{IC}, results that the critical crack depth is:

$$\alpha_{cr} = 1.62 \text{ mm}$$

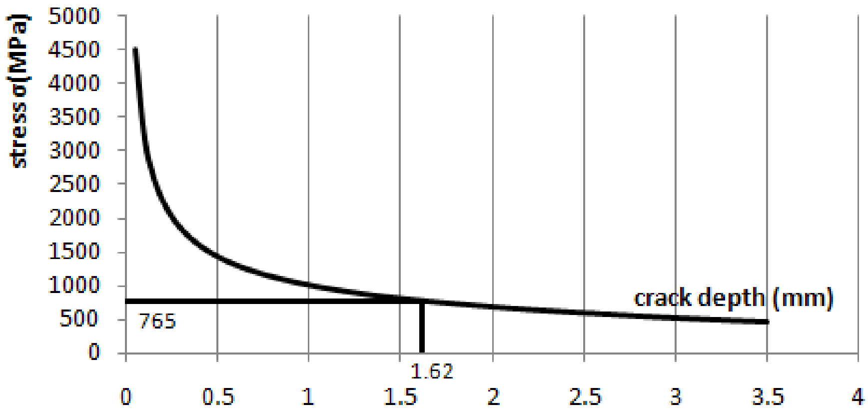


Figure 5. Critical crack depth for σ_m

4.3 Determination of microscopic and macroscopic material parameters

Table 2. Mechanical parameters of steel wire

Elastic modulus E_{macro}(GPa)	Shear modulus μ_{macro} (GPa)	Poisson's ratio ν_{macro}	Ult. strength σ_{ult}(MPa)	Ultimate strain ε_{uk}
210	80.8	0.3	1770	≥20‰

The material parameters depend of the scale. The macroscopic parameters are presented to the *Table 2.* For the microscopic parameters assume that:

$$\nu_{micro} = 0.4 \,,\ d_0 / r = 1.0 \,,\ d_0 = 10^{-3} mm$$

Also, for the material fatigue parameter C_0 assume that:

$$C_0 = 3.5x10^{-4} \frac{mm^2}{N}$$

4.4 Modes crack growth

With the fatigue crack growth, the crack depth a gradually increases from microscale to macroscale. The three basic ratios d*,μ* and σ* are inserting into determination of crack growth when the crack is $\alpha < 1.62$ mm. Intended three different Modes (Mode A – Mode B – Mode C) to the determinate the ratios d*,μ* and σ*. The variation of d*, μ* and σ* according to three modes is shown in *Fig. 3-4* and *5*.

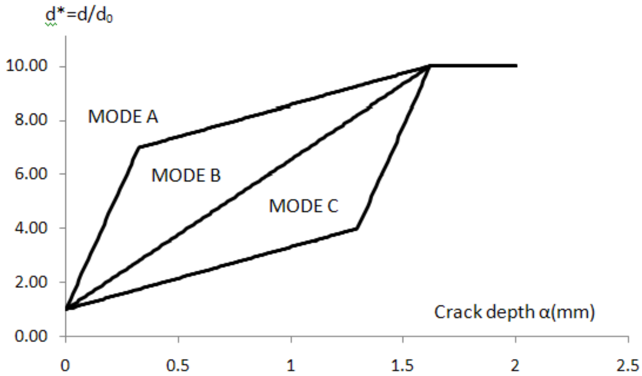


Figure 6. Change of length d^* ratio with crack depth

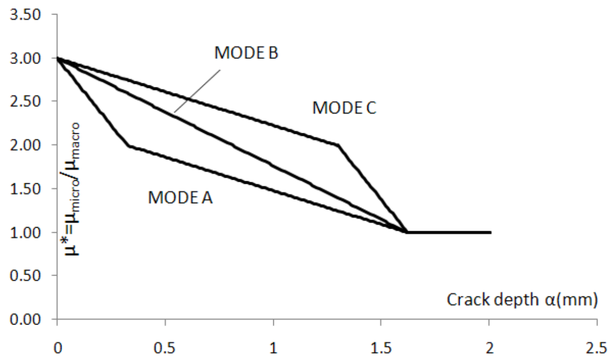


*Figure 7.*Change of modulus μ^*

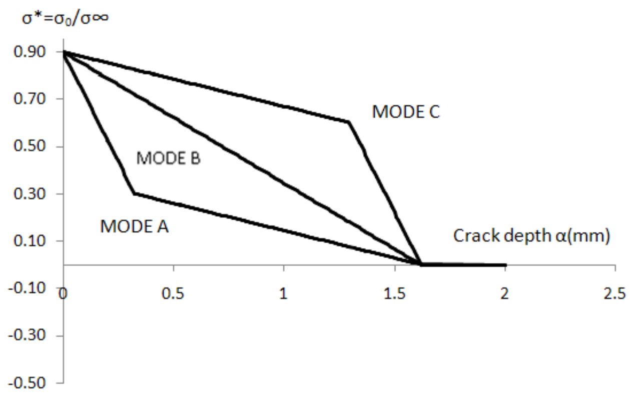


Figure 8. Change of stress σ^* ratio with crack depth

4.5 Influence of initial crack size

This chapter focuses on the effect of the initial crack size to the crack depth by cyclic number N.

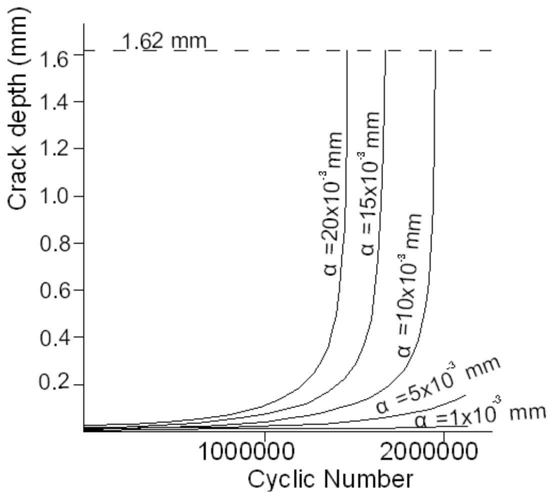


Figure 9. Case I (A=1.0) & Case II (B=1.0)

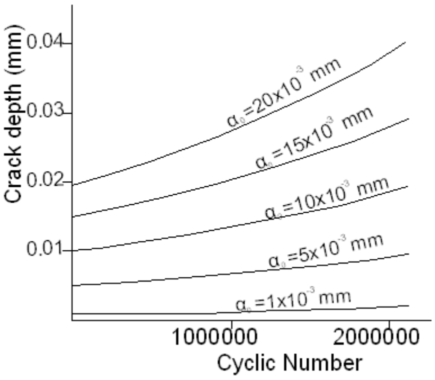


Figure 10. Case I (A=0.85)

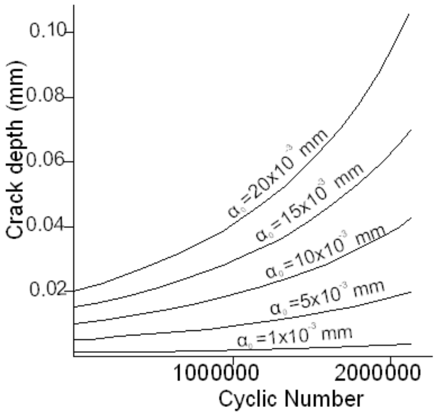


Figure 11. Case I (A=0.9)

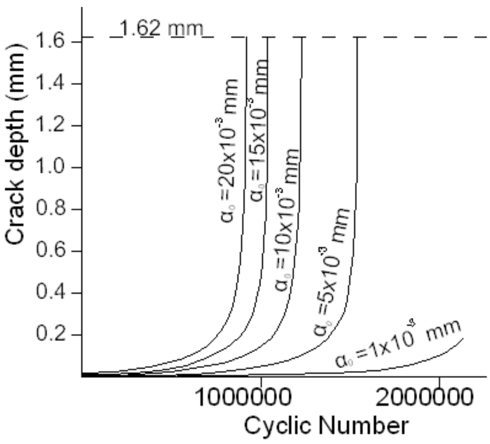
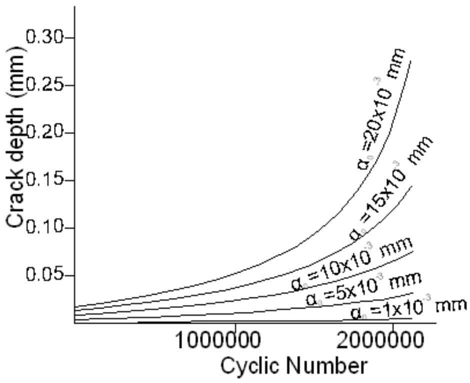


Figure 12. Case I (A=1.1)



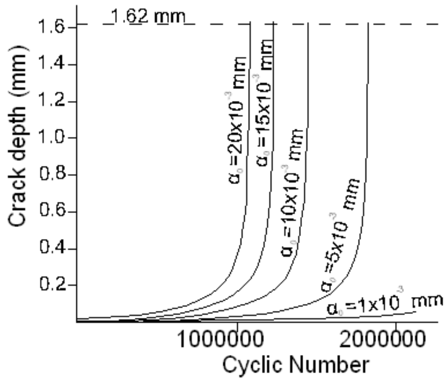


Figure 13. Case II (B=1 !*4.* Case II (B=0.9)

5 CONCLUSIONS

The problem of fatigue is of vital importance for the life expectancy of a bridge, especially for a cable-stayed bridge. According to the mesoscopic fracture mechanics from this paper for this particular bridge the following results have emerged:

- The extent of the initial crack is of immense importance for the life expectancy of the bridge.
- In normal stress (A=1) for Case I the examined cable fails in less than two million circles of load if the first crack exceeds $\alpha_0 \geq 10x10^{-3}$mm In Case I if the value of coefficient A>1.1 the wire fails in less than two million circles if the first crack exceeds $\alpha_0 \geq 5x10^{-3}$mm . This means that the tightening factor has negative effect, conversely the loosening factor A<1.0 has positive effect as even for A=0.85 and initial crack $\alpha_0 = 20x10^{-3}$mm the wires exceed two million.
- In Case II for the value of coefficient B=0.9 the wire fails in less than two million circles for initial crack $\alpha_0 \geq 5x10^{-3}$mm where as for B=1.1 the wire fails in less than two million circles for initial crack $\alpha_0 \geq 20x10^{-3}$mm.This means that the loosening factor has negative effect in Case II and that the tightening factor has positive effect.

According to this research the control of the cable wires with initial cracks is considered as a critical factor in order to predict the number of circles and as a result the life expectancy of a wire as well as its replacement.

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