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Mechanics of environment-assisted cracking in bridge cable wire

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Broken wires retrieved from suspension bridge cables display a wide range for the critical crack sizes and corresponding ultimate strength. During tensile tests, most specimens fracture at short crack depths at a strength lower than the yield strength. This paper presents the analysis of environment-assisted short crack growth in bridge wire. It will be shown that the degrading environment in the bridge cable causes the reduction in the fracture toughness of the wire at the short crack location leading to brittle fracture. The paper will present a case study of short cracks observed during laboratory testing of bridge wire samples which failed at tensile loading below the maximum yield strength. The paper confirms the validity of linear elastic fracture mechanics in the analysis of environment-assisted short crack growth in the bridge wire at fracture. It is shown that the effective fracture toughness, $(K_C)_M$, at a short crack location could be significantly reduced due to environmental degradation. The fracture toughness criterion is utilized to forecast the degraded strength of cracked wire. Crack branching is shown to have no role in the mechanism of crack growth in the high strength steel bridge wire.

Keywords: Linear elastic fracture mechanics; Environment-assisted cracking; Bridge cable wire; Environmental degradation; Hydrogen embrittlement; Stress-corrosion cracking; Net section criterion

1. Introduction

In many fracture applications, the role of sub-critical crack growth is of major importance (Tiffany and Masters 1965). This is manifested in the high strength steel bridge wire, where the environmental degradation may cause apparently innocuous cracks to grow until they are of a size sufficient to cause failure. A basic principle of fracture mechanics is that unstable fracture will occur when the stress intensity factor at a crack tip reaches a critical value, which defines the fracture toughness. Although this critical value will depend upon many factors, including thickness, chemical composition, and heat treatment, it is possible to determine the fracture toughness of the wire, K_C, by appropriate experimentation (Bridge Technology Consulting 2007). Since an analytic formulation of the stress intensity factor contains parameters representing the crack variables, such as shape and size, and also the loading variables, it follows that the critical stress intensity factor represents a critical combination of applied stress and flaw size. From the viewpoint of short crack growth, it is more appropriate to note that the critical crack size corresponds to a critical combination of applied stress and fracture toughness as described by the critical stress intensity factor. One of the primary causes of sub-critical crack growth is aggressive environments (Johnson and Paris 1967). The effect of environmental conditions is therefore essential in the analysis of cracked wires and the true definition of short and critical crack growth in bridge cable wires. It is important to note that experimental results have shown

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that some materials are highly resistant to stress corrosion in smooth specimen tests. However, they are vulnerable to stress corrosion cracking when pre-cracked specimens are tested under similar conditions (Brown and Beachem 1965).

In situ wire breaks with crack depth to diameter ratio, (a/D), of up to 0.5 have been retrieved from bridge cables, where a is the crack depth and D is the wire diameter. These cracks have evidently grown to a critical depth, a_c, which corresponds to a strength capacity lower than the applied stress in the wire leading to its fracture. Fracture surfaces demonstrate initial cracks which propagate transversely across the wire until an unstable condition is reached and brittle fracture occurs. Depth ratios of cracks, observed in wires that broke in service, display a minimum $(a/D) \approx 0.27$, and a maximum (a/D) of up to 0.5. On the other hand, cracks that are observed in wire test samples are, for the most part, shallower than 0.25 (a/D), and therefore classified as sub-critical, or short cracks.

The analysis of cracked wires in bridge cables has received little attention in the past and the collected data for crack depths is limited. Recently, more focus has been directed towards fracture analysis of bridge cable wires (Mahmoud and Fisher 2003, Gjerding-Smith *et al.* 2006, Mahmoud and Moreau 2006, Mahmoud 2007). The evaluation of the strength capacity of cracked wires at fracture is important in the assessment of bridge cable strength due to the cracked wire distinct behavior, which is evident in the low ultimate elongation of cracked wires. If cracked wires were lumped with intact wires, the remarkable low ductility of cracked wires would not be fully demonstrated. This could result in a significant overestimation of the cable strength. Thus the categorization of wires in the bridge cable into cracked and intact is of paramount importance in the accurate modeling and representation of true cable behavior.

In this paper, the mechanics of short crack growth in the high strength steel wire of bridge cables are discussed. A case study of a group of cracked wires sampled from a suspension bridge cable and their fracture resistance will be presented and the role of the degrading environment will be highlighted. Forecast of the wire strength at fracture will be assessed based on the fracture toughness criterion. The phenomenon of crack branching will be discussed and shown not to occur in the high strength steel bridge cable wire.

2. Short cracks in bridge wires

The influence of the environment on the strength of high strength steel bridge cable wire has received little attention from a fracture mechanics viewpoint. The phenomenon of local failure at the tip of a crack in the wire, causing the growth of initial cracks and eventual failure of the wire is manifold and complex. The primary task of the theory is to combine the individual mechanisms of local failure and create sufficiently simple and reliable mathematical model for the entire process. It has been recognized that the strength and deformation capacity of solids depend on the environment in which they operate. The influence of the environment on the high strength steel bridge wire is manifested in the strength degradation and the pronounced brittle behavior of the wire. Microscopic quantities of pollutants could be sufficient to change the strength of the wire significantly. A change in external conditions has a strong effect on processes of local failure at the tip of a crack. Therefore crack growth rate as a function of external parameters is a significant factor in the material–environment system. In a suspension bridge cable, the live load fluctuation is typically minimal, and therefore the effect of external load parameters is inconsequential. However, short crack growth in bridge cable wire is evident from the available test data. Thus, the phenomenon of short crack growth in the wire should be described within the framework of the fracture toughness, K_C, concept. This could be achieved by studying the degradation in the fracture toughness of the wire material under the influence of the environment. Bridge cable wire is made of much higher yield and tensile strength steel than typical structural members, therefore it is more susceptible to environment-assisted cracking. Moreover, environmental conditions within suspension bridge cables, including trapped moisture and partial or complete loss of galvanized coatings, promote chemical reactions that charge hydrogen into the wire. These reactions, in combination with surface attack and pitting that produce stress concentrations, lead to flat transverse stress corrosion cracks in wires. Stress corrosion and hydrogen embrittlement have been reported to cause cracking in high strength steel suspension bridge cable wire as the sacrificial loss of zinc coating from oxidation and access water into the cable have caused pitting and the formation of cracks that subsequently grow and fracture wire. The cracking sequence observed in a number of suspension bridges usually starts with a corrosion pit, followed by a growing part-through transverse flat crack. When cracking reaches a critical depth, usually about half the wire diameter, failure of the wire occurs. The failure is sometimes accompanied by longitudinal splitting of the wire (Fisher *et al.* 1998).

The process of sub-critical failure under stress can be divided into two periods: the incubation period which defines the interval of time during which the crack is formed, and the period of the sub-critical crack growth. This paper will address the growth phase of sub-critical cracks, which will result in fracture in bridge cable wire.

The rate of sub-critical crack growth, $\frac{da}{dt}$, is a function of the stress intensity factor, K, such that:

$$\frac{da}{dt} = f(K) \tag{1}$$

The function described by equation (1) is equal to 0 when $K_I \leq K_{EAC}$, while when $K_I \leq K_{EAC}$, the function increases monotonically with increasing K_I. The ratio of $\frac{K_{EAC}}{K_C}$ for ductile metals is usually close to 1. For high strength steel materials and brittle alloys, such as the bridge cable wire, the ratio of $\frac{K_{EAC}}{K_C}$ could be much less than 1, depending on effect of the environment at the short crack location. The quantity K_{EAC} is defined as the threshold stress intensity factor for environment-assisted cracking. It is important to emphasize that there is no implied relationship between the fracture toughness and resistance to environment-assisted cracking (Johnson and Paris 1967). It is also worthy of note that some recent work on suspension bridge cable wire has shown degradation due to the effect of hydrogen embrittlement (Service *et al.* 2004, Gjerding-Smith *et al.* 2006, Bridge Technology Consulting 2007). The ASTM E1681-03 Standard Test Method for Determining a Threshold Stress Intensity Factor for Environment-Assisted Cracking of Metallic Materials, Volume 03.01, developed by Subcommittee E08.06, provides the procedures for the measurements of K_{EAC} (ASTM E1681-03 2003). The specification adopts the more general quantity K_{EAC} instead of the traditional K_{ISCC}. The K_{ISCC} value for a specific material–environment system at a given temperature is defined as the threshold stress intensity factor, under which sub-critical crack growth does not occur under sustained loads in the environment.

Due to size limitations of the bridge wire, the following methodology is proposed to evaluate K_{EAC} for the bridge cable wire.

3. Proposed methodology for identification of K_{EAC} for bridge wire and practical implications

The ideal case is to establish experimentally a minimum value for the quantity K_{EAC}, above which the growth of a short crack in a bridge wire occurs. A pre-cracked wire specimen surrounded by corrodent solution should be loaded at initial stress intensity somewhat lower than that required for dry break and the time to fracture noted. The stress intensity required for dry break is defined by the fracture toughness of suspension bridge cable wire, K_C, which was first measured by Bridge Technology Consulting (2007). Successively, lower initial stress intensities are to be used until a specific level of stress intensity is reached, which is insufficient to propagate the crack during the test. From these data one can readily arrive at the minimum stress intensity required to propagate the crack, K_{EAC}. It is of paramount importance to note that from this proposed methodology, one cannot state that a crack will never grow at a stress intensity lower than the observed K_{EAC}, because an extension of the time of the test by one or two orders of magnitude might result in crack growth. There is no available data for crack growth in wire to date. It is assured, however, that initial stress intensity higher than K_{EAC} will cause crack growth due to the effect of the environment at the crack location. Therefore in conducting the test, it is of significance to establish a rough idea of maximum testing time required to be reasonably sure that environment-assisted cracking will not occur at a given value of the quantity, K_{EAC}.

It must also be noted that the environment-enhanced crack growth is governed by the material–environment system which involves the effect of relative humidity, temperature, and hydrogen diffusion (Mahmoud 2003). As soon as the applied stress intensity factor, K_I, exceeds the threshold stress intensity factor for environment-assisted cracking, K_{EAC}, short crack growth ensues. The short crack growth will continue until the applied stress intensity factor, K_I, reaches a critical value and wire fracture occurs. The critical value of the stress intensity factor is strongly related to the local environment at the short crack location. Thus, it is perceivable, under the effect of the environment, that a certain level of the stress intensity factor, K_I, may lead to the fracture of the wire at a short crack of a given size in a wire inside the bridge cable. However, under less aggressive environment, the same value of K_I might not lead to the fracture of another wire that contains a similar size short crack. The apparent practical implication of this hypothesis is that wires that contain short cracks which were developed in-service would display a range for the critical value of the stress intensity factor at fracture depending on the local environment at each short crack.

In the following section, a case study is presented for a group of cracked wires retrieved from a major suspension bridge cable, and the concept of effective fracture toughness at short cracks is established.

4. Case study of short cracks in suspension bridge cable wire

In this section, a case study of the short crack behavior for a group of wires retrieved from a main suspension bridge cable is presented. Before proceeding with the analysis of short crack growth, the analysis and definition of critical crack depth threshold for bridge wire are introduced. Analysis within linear elastic fracture mechanics is compared with the net section criterion, to account for the plastic deformation ahead of the crack tip.

4.1 *Fracture analysis*

In situ wire breaks with crack depth ratio, (a/D), of up to 0.5 have been retrieved from bridge cables. These cracks have evidently grown to a critical depth, a_c, which corresponds to a strength capacity lower than the applied stress in the wire leading to its fracture. It is established that in situ wire breaks demonstrate initial cracks which propagate transversely across the wire until critical depth, a_c, is reached, and (quasi) brittle fracture occurs. Depth ratios of cracks, observed in wires that broke in service, display a range of crack depth ratio, (a/D), that varies between 0.27 and 0.5. Figure 1 shows a low magnification (× 11) scanning electron microscope (SEM) micrograph for a wire break with a straight crack front and $(a/D) \approx 0.5$. The dashed line in Figure 1 was drawn by the testing laboratory to define the front of the critical crack along which the failure occurred. On the other hand, an aggressive environment could invoke fracture in a wire that contains a short crack, as seen in Figure 2.

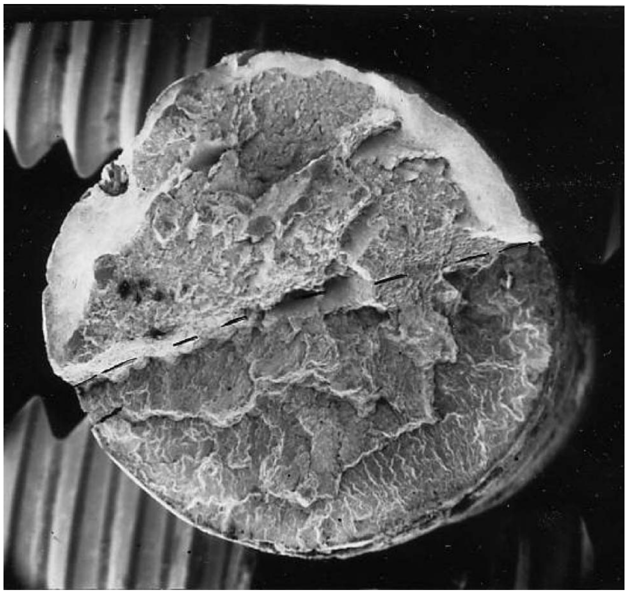

Figure 1. Wire break with straight crack front and critical depth ratio, $(a/D) \approx 0.5$.

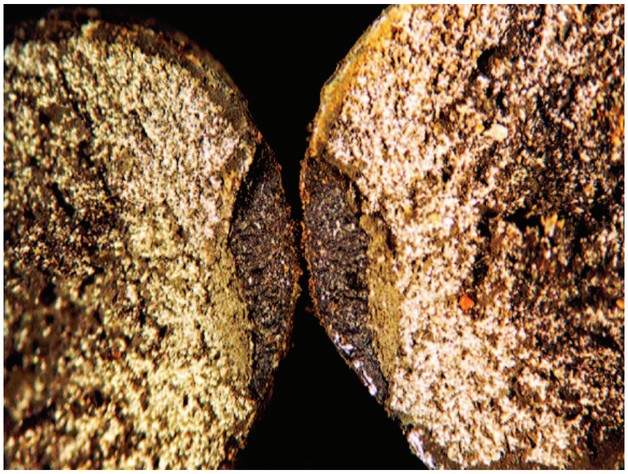

Figure 2. Wire break with semicircular short crack.

Cracks that are observed in non-broken wire test samples are, for the most part, shallower than 0.27 (a/D). Therefore, cracks with depth ratio lower than 0.27 will be regarded as sub-critical or short cracks in the 5-mm suspension bridge cable wire. With this definition, most of the cracks detected in bridge wire samples are classified as sub-critical, or short cracks. It is important to note that wire fracture could take place at a short crack depth when the applied stress intensity factor, under the effect of local environment, reaches a critical value, as defined below.

Cracked wire data retrieved from many suspension bridges shows an increasing trend of short crack growth with the passage of time. This indicates a crack growth rate that could eventually reach the critical crack depth ratio, as observed in the in situ breaks, leading to the wire fracture. However, the time for this to occur is not known. In the short crack domain, if the applied stress intensity factor exceeds the quantity K_{EAC}, short crack growth occurs. When the stress intensity factor at a given crack location reaches a critical value, $(K_C)_M$, wire fracture occurs at a short crack depth. The quantity $(K_C)_M$ required to cause fracture at a short crack depth depends on the environment – material system, which includes the effect of degrading medium, temperature and relative humidity at the short crack location. The above-described mechanism could be explained in light of the well-known phenomenon of delayed fracture that factors in the concentration of atomic hydrogen at the mouth of the crack (Mahmoud 2003). The material – environment system parameter, $(K_C)_M$, could be defined as the effective fracture toughness at a given short crack location. The value of $(K_C)_M$ is given by making use of the following formulation:

$$(K_C)_M = \sigma_C \cdot Y\left(\frac{a}{D}\right) \cdot \sqrt{\pi \cdot a_{sub-c}} \tag{2}$$

where σ_C is the fracture strength of a wire with short crack depth of a_{sub-c} and $Y\left(\frac{a}{D}\right)$ is the crack shape parameter for the wire under tension, given by (Mahmoud 2007):

$$\begin{aligned} Y\left(\frac{a}{D}\right) &= 0.7282 - 2.1425\left(\frac{a}{D}\right) + 18.082\left(\frac{a}{D}\right)^2 \\ &\quad - 49.385\left(\frac{a}{D}\right)^3 + 66.114\left(\frac{a}{D}\right)^4 \end{aligned} \tag{3}$$

For a group of cracked wires that were retrieved from a suspension bridge cable and tested in tension, the fracture strength, σ_C, and the short crack depth were measured and recorded for each wire specimen. Figure 3 displays the relationship between the effective fracture toughness due to environment-assisted cracking, $(K_C)_M$, and crack depth to diameter ratio, (a/D). The figure demonstrates a strong correlation between the two parameters. The data point at the far bottom right corner of Figure 3 was taken from a broken wire and reported a very low fracture strength.

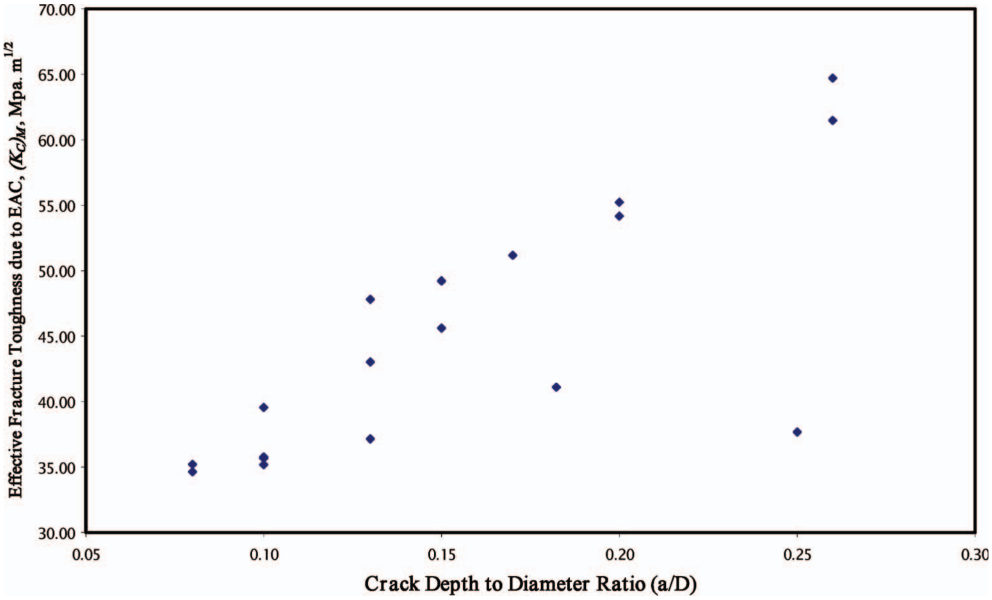

Figure 3. Range of the effective fracture toughness due to environment-assisted cracking, $(K_C)_M$.

Exclusion of that anomalous point results in a stronger correlation between $(K_C)_M$ and (a/D).

The observed range associated with this set of data is $34.64-64.71\ \mathrm{MPa \cdot m^{1/2}}$, whose maximum bound is less than the recently evaluated fracture toughness of the suspension bridge cable wire of about $65.70\ \mathrm{MPa \cdot m^{1/2}}$ (Bridge Technology Consulting 2007). It is worthy of note that all the values of the fracture strength, σ_C, for this set of data, with the exception of three specimens, were below the maximum value of the yield strength measured for the cable wire. One of these three specimens reported a fracture strength that is very close to the average strength of intact, i.e., non-cracked wires. This raises questions about the sharpness of the crack in that specimen. There are no SEM images to confirm the presence of cracks in that specimen. It is likely, however, that the specimen contained corrosion pits that was not sharp enough to grow a crack. The above analysis validates the computation of the fracture capacity for cracked wires within the scope of linear elastic fracture mechanics.

Ideally, to evaluate the fracture strength for a cracked wire inside the cable, the effect of the environment–material system should be precisely known to determine the effective toughness, $(K_{EAC})_M$, at a given short crack. In addition, the depth of the short crack should also be known. This is, however, very difficult to establish and to account for in the real cable due to the differences in the effect of the environment–material system at different short cracks along the cable length. A viable and practical approach is to infer the fracture strength based on the measured dry fracture toughness, K_C, and the relevant crack depths within linear elastic fracture mechanics. Relevant crack depths are those which will result in fracture stress lower than the yield strength. The benefit of this approach is that the fracture strength could easily be established using a measurable material property: the fracture toughness, K_C. The latter has been shown to provide a practical means for the calculations of the strength degradation of a cracked wire, as will be demonstrated later (Mahmoud 2007). Therefore the employment of the fracture toughness, K_C, criterion is of significant and practical importance.

4.2 *Net section criterion*

The fracture surfaces of cracked wires exhibit quasi cleavage (brittle) failure with negligible ductility. As has been mentioned earlier, most of the wire fractures took place under the yield strength of the wire material. To demonstrate the negligible effect of plastic deformation in cracked wires, the net section theory is introduced. The net section capacity is a conventional method that is widely used to estimate the strength of structural components under plastic collapse conditions (Mahmoud 2007). The critical nominal stress, σ_{Cr}, is calculated from:

$$\sigma_{Cr} = \frac{A_{Net}}{A}\sigma_f \tag{4}$$

where A is the nominal cross-sectional area, $A_{Net} = A - A_{Crack}$ is the net section area, with A_{Crack} being the area occupied by the crack, while σ_f is an assumed material property known as the flow stress, and is taken as the average of yield and ultimate stresses.

Equation (4) assumes that the stress distribution is uniform tension across the net section of the wire at the failure state. This hypothesis is well justified by the known tendency of plastic deformation to smooth out uneven stress distribution across the uncracked surface.

The average critical nominal stress, σ_{Cr}, using the net section theory is only 6% higher than the average fracture strength calculated based on linear elastic fracture mechanics. For the particular case presented here, this translates into mere 0.4% less force capacity, or 1% on the factor of safety. Obviously, this confirms the observation that the limited plastic behavior effect on the assessed cable strength and factor of safety is negligible.

It should be realized that the plastic solution using the net section criterion could render unconservative results for the fracture capacity of a wire with deep crack. In other words, it would lead to a significant overestimation of the cable strength. For the cracked wire shown in Figure 1, for instance, the crack depth to diameter ratio, $(a/D) = 0.46$. This corresponds to fracture strength of 449 MPa, using linear elastic fracture mechanics, whereas the net section capacity produces fracture strength of 738 MPa. The value of the dead load stress in the wire, at the suspension bridge from which the wire was retrieved, has been calculated as 482 MPa. As soon as the crack depth to diameter ratio, (a/D), reached the value of 0.46, the dead load stress exceeded the wire fracture strength, calculated using linear elastic fracture mechanics, leading to the wire fracture. Evidently, in this case, the wire fracture strength is not governed by the net section fracture capacity of 738 MPa, which exceeds the dead load stress in the wire. The overestimate in the fracture capacity of the wire in this particular case is significant.

In the final analysis, plastic deformation as demonstrated by the net section theory overestimates the factor of safety if used for the full range of crack depths. In other words, the use of linear elastic fracture mechanics results in negligible effect on the fracture capacity of cracked wires, whereas the use of plastic approach could significantly overestimate the cracked wire strength. On balance, the use of elastic fracture mechanics with relevant crack depths proves as the best available methodology to determine the fracture strength of cracked wires in the cable.

In the next section, the minor role of crack branching in bridge cable high strength steel wire is highlighted.

5. Use of toughness criterion to forecast fracture strength of cracked wire

Fracture toughness degradation due to environmental factors has been observed in high strength steel wire (Gjerding-Smith 2006, Bridge Technology Consulting 2007). The degradation of toughness has been correlated to the strain energy density for bridge wire (Mahmoud 2007). The strain energy density criterion was developed in 1970s as a rational approach to linear elastic fracture mechanics and was also shown to be applicable to ductile fracture (Sih and Madenci 1983). In recent experimental work (Bridge Technology Consulting, unpublished results), the fracture toughness for the new bridge wire was evaluated at $76.65\ \mathrm{MPa \cdot m^{1/2}}$ to quantify the adverse effects of degradation on the deteriorated wire toughness. Assessment of the strain energy density evaluated from the stress–strain curve of the wire follows the work in (Jeong *et al.* 1995). A relationship between the toughness and the strain energy density for a bridge wire was first proposed by (Mahmoud and Kassir 2003) as follows:

$$K_c^2 = \beta \cdot W_0 \tag{5}$$

Where β is a function of the elastic properties of the wire material that will be considered constant with exposure to the environmental degradation. The fracture toughness of the degraded wire, $(K_c)_d$, is correlated to the fracture toughness of the healthy (new) wire, $(K_c)_h$, by the following relationship:

$$(K_c)_d^2 = (K_c)_h^2 \cdot \frac{(W_0)_d}{(W_0)_h} \tag{6}$$

Where $(W_0)_d$ and $(W_0)_h$ are the strain energy density for the degraded and healthy wire, respectively.

The fracture toughness measurements of the degraded wire along with the strain energy density criterion allow for the calculation of the fracture strength of cracked wires at a given time in the future by use of the typical stress strain curve produced by the conventional tension test. This affords the practicing engineer a simple tool for forecasting the fracture strength of cracked wire proportion in the bridge cable.

6. Crack branching in high strength steel bridge cable wire

The first analysis treatment in fracture mechanics to include the effect of inertia forces on crack propagation was also the first to attempt a quantitative treatment of crack branching. This was the 'moving Griffith crack' solution of (Yoffe 1951). Yoffe considered a crack propagating in an infinite elastic region under a uniform applied stress acting normal to the crack line. The special feature of Yoffe's analysis was that the crack retains its original length. In essence, it is a disturbance that propagates at a constant speed without change of form. While physically unrealistic, it did at least provide an indication of the influence of crack speed on the stress state at the tip of a rapidly propagating crack. Yoffe was motivated by the idea that while the stresses about a stationary crack are such that crack extension will occur in the line of the crack, there might be a tendency for the crack to curve or branch at high propagation speeds. The next important dynamic crack propagation solutions were those contributed by (Broberg 1960, Craggs 1960). Broberg argued that, if the surface energy is negligibly small, then the crack will nucleate from an infinitesimally small microcrack and will achieve the limiting velocity immediately. He therefore solved the dynamic problem of a crack expanding from zero length at a uniform rate. Baker (1962) subsequently generalized Broberg's solution to include a finite initial crack.

All of the above solutions are artificial solutions that have no direct structural applications. Even though crack branching offers attractive research opportunities to mathematicians and experimentalists, its practical applications are not of nearly as much significance (Kanninen and Popelar 1985). In 1966, Clark and Irwin (1966) provided a practical solution to the problem. They found that the crack speed just before crack division was nearly the same as that of the most advanced crack in a multiple division crack pattern. Hence, in contrast to Yoffe's argument, the crack does not branch solely because it reached some critical velocity. Clark and Irwin were able to arrive at an alternative explanation through estimates (quasi-static) of the crack driving forces prior to and following branching. Upon finding them to be nearly equal, they concluded that 'it seems best therefore to regard attainment of a critical K (or G), rather than a crack-speed-induced modification of the stress pattern, as the primary factor controlling crack division'.

It has been established that simultaneous growth of many parallel cracks is unstable. As soon as, for some random reason, one of the cracks gets slightly ahead of the rest, the stress intensity factor of the leading crack becomes greater than that of the others and, consequently, the growth rate of this leading crack increases. At the same time, the stress intensity factor and growth rate of the neighboring cracks decrease. This effect is more pronounced the greater the lead taken by the leading crack, so that finally the most dangerous (leading) crack remains as the only one (Cherepanov 1979).

Based on experimental study for many high strength steel alloys (Carter 1971), it has been shown that that when (K_{ISCC}/K_C) exceeds 0.5, rapid brittle fracture will occur before the stress intensity factor for crack branching, K_{Ib}, can be reached. In the study, the condition for crack branching has been established by the following inequality:

$$K_{Ib} \geq 2\ K_{ISCC} \tag{7}$$

The high strength steel used for bridge wire is similar in its properties to the H11-Alloy high strength steel whose yield strength is 1295 MPa, and fracture toughness is $59.10\ \mathrm{MPa}\cdot\mathrm{m}^{1/2}$. The threshold stress intensity factor for stress corrosion cracking, K_{ISCC}, of $32.85\ \mathrm{MPa}\cdot\mathrm{m}^{1/2}$ was determined for H11-Alloy high strength steel (Carter 1967). Bridge Technology Consulting has recently measured the fracture toughness for the Mid-Hudson Bridge wire at $65.70\ \mathrm{MPa}\cdot\mathrm{m}^{1/2}$ (Bridge Technology Consulting 2007). Therefore it is reasonable to assume that the stress intensity factor threshold, K_{ISCC}, for the wire is approximately $32.85\ \mathrm{MPa}\cdot\mathrm{m}^{1/2}$.

With the above values for K_{ISCC} and K_C, for the H11-Alloy, it was not possible for the stress intensity at the tip of the extending crack to reach the critical level for branching ($K_{Ib} > 2K_{ISCC}$) before the onset of rapid brittle fracture at K_C. Similarly, for the high strength steel wire material whose properties are almost identical to the H11-Alloy high strength steel, crack branching will not occur as (K_{ISCC}/K_C) does not exceed 0.5.

The influence of the microstructure in fracture mechanics is referred to by the random factor. When $K_I < K_{Ib}$, the initial random fractures at the front of a crack resulting from uniform pitting and the influence of the external field do not grow beyond the limits of action of random factors of the microstructure (on the order of the grain size). Therefore, small microcracks at the front of a crack cannot be related to the phenomenon of crack branching; their growth is explained by the electrochemical mechanism of the growth of pits and cracks (Cherepanov 1979).

Occasionally, a longitudinal split or line of discontinuities has formed in a wire during manufacture. When these conditions exist at a crack location, the crack extension will arrest when it encounters this zone. This is not a branching crack but the intersection of a propagating crack with this anomaly (Pense *et al.* 1997).

The above discussion asserts the well-known notion that crack branching does not take place in bridge cable wire.

7. Conclusions

Short crack growth mechanism in the high strength steel wire of suspension bridge cable was introduced. The brittle behavior of cracked wire allowed the calculations of the fracture strength using linear elastic fracture mechanics. Comparison with the net section criterion, to account for the marginal plastic deformation ahead of the crack tip, provided only negligible increase in the structural capacity of wires that contain short cracks. A methodology for the evaluation of the threshold stress intensity factor for environment-assisted cracking in wire, K_{EAC}, was proposed. The paper provided the definition of effective fracture toughness at the short crack location, $(K_C)_M$, which is affected by the local material – environment system at the crack location. Forecast of degraded wire strength is proposed based on the strain energy density approach. Analytical and experimental evidence from analysis of wire breaks show no role for crack branching in the mechanism of crack growth in the high strength steel wire of bridge cables.

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