

# An absorbing process

A new way of assessing the residual strength in bridge cable wire is being applied in the USA. *Khaled Mahmoud* explains the process and its application

**A**ssessment of the safety evaluation of bridge cables does not usually account for the effects of the corrosive environment, and sustained and cyclic loadings. Environmental degradation is dependent on the interaction between loading, environmental and metallurgical factors, and this interaction increases the rate of growth of transverse cracks in wires under tension. Deterioration of cable wires takes different forms; stress corrosion cracking, pitting, corrosion fatigue and hydrogen embrittlement, which compromise the strength and ductility of wires leading to a reduced service life of bridge cables.

The traditional four stages of corrosion are qualitative and do not provide a quantitative assessment of the corrosion severity. In addition, hydrogen embrittlement of cable wires cannot be detected using this method.

Hydrogen embrittlement occurs when the component is being protected from corrosion, or when the steel is cathodically protected. The cathode potential will usually be such that some atomic hydrogen will be deposited on the surface of wires. Although molecular hydrogen is insoluble in steel at ambient temperatures and pressures, atomic hydrogen can diffuse into the steel, and this weakens the interatomic bond of the wire high strength steel. The hydrogen moves towards zones of high tensile stress, for example, crack tips in cable wires.

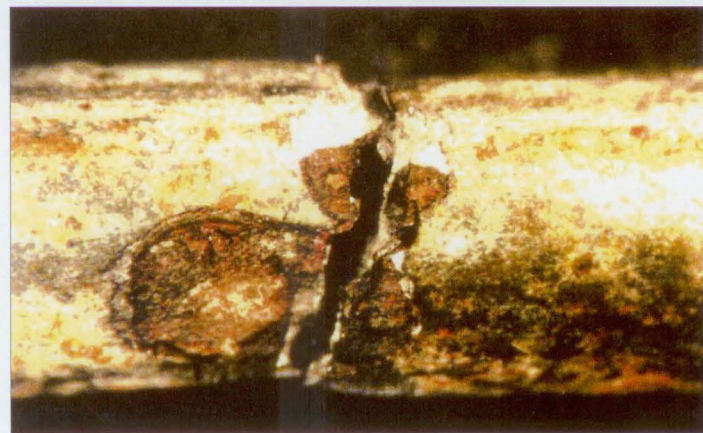
Hydrogen generated by the corrosive action of hydrogen sulphide in high strength steel cable wires causes embrittlement, cracking and failure.

The earliest examples of a unique fracture mechanism, now known as 'delayed failure' or hydrogen-assisted cracking, were observed in cadmium-plated steel aircraft parts with yield strengths of 1100 to 1240MPa. These failures occurred at relatively low static loads, even though the same parts had previously withstood much higher dynamic loads. The fractures appeared to be brittle, but tensile specimens machined from failed parts exhibited normal ductility and strength in the conventional tensile test.

It was also characteristic that these parts had absorbed hydrogen during some manufacturing process. Wires taken from suspension bridge cables and tested in the laboratory demonstrate a similar behaviour.

The loss of ductility, due to environmental deterioration, is not always manifested in a wire cross-sectional area reduction. On the contrary, under the influence of hydrogen embrittlement, the area reduction may be quite inconsequential, while the ductility loss is significant. The images on this page demonstrate a fractured wire specimen with minimal necking. The stress-strain curve of the same specimen reveals a significant reduction in elongation at failure. In this case, reduced ductility, along with virtually non-reduced cross-section, is suggestive of a hydrogen embrittlement regime of fracture. The opposite page shows a wire specimen with a typical cup and cone fracture. The elongation, though about one-third of a new wire, is almost double that of the embrittled wire shown on this page, more suggestive of a stress corrosion mode of failure. This indicates that the effect of hydrogenation is mirrored in the reduced ductility of the wire material and not in the effective cross-sectional area.

The presence of broken/cracked wires and the loss of ductility are indicative of a higher rate of deterioration of cable strength than that inferred from only the loss of the wire cross-sectional area. It is therefore reasonable to conclude that the conventional methods of calculating cable strength by

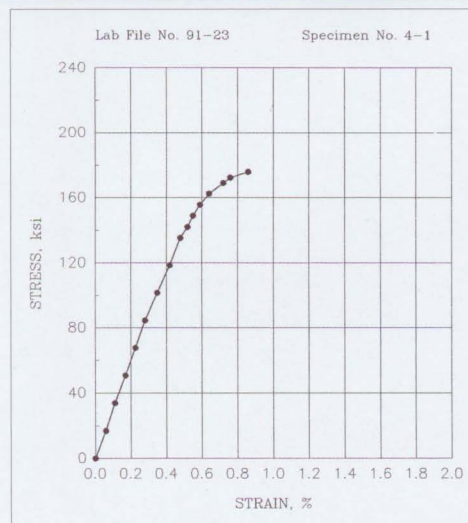


Hydrogen embrittlement showing;

Top: Tension specimen with low ductility

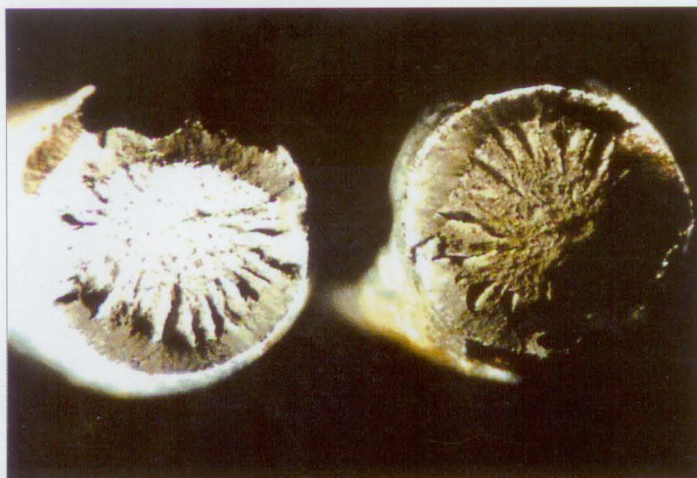
Middle: Side view with minimal necking

Right: Stress-strain curve



summing the strength of all the wires, without accounting for the loss of ductility of the wire material, overestimate the true factor of safety for bridge cables. Very little work has been done on the quantification of cable wire deterioration due to stress corrosion and/or hydrogen embrittlement. The presence of cracked wires underlines the importance of a fracture-based analysis of cables. In the traditional approach to structural design, the two major variables under consideration are the material strength and the applied stress. The component is assumed to be adequate if its strength is greater than the expected applied stress. Such an approach guards against brittle fracture through the introduction of a safety factor. In the presence of a flaw, however, fracture can occur at stresses below the material's yield strength and even at the allowable design stress. In fracture analysis, an additional variable to consider is the flaw size, and fracture toughness replaces material strength as the relevant material property.



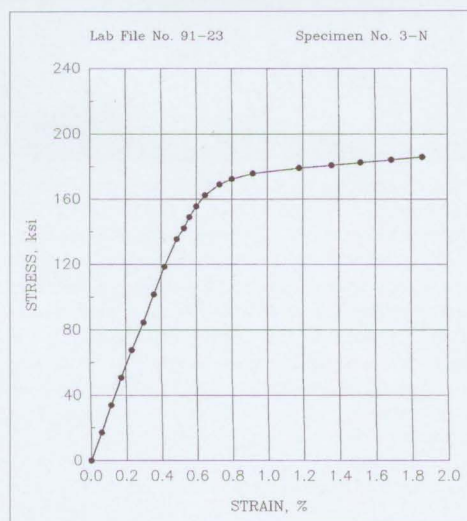


Stress corrosion cracking showing;

Left: Tension specimen with cup & cone fracture

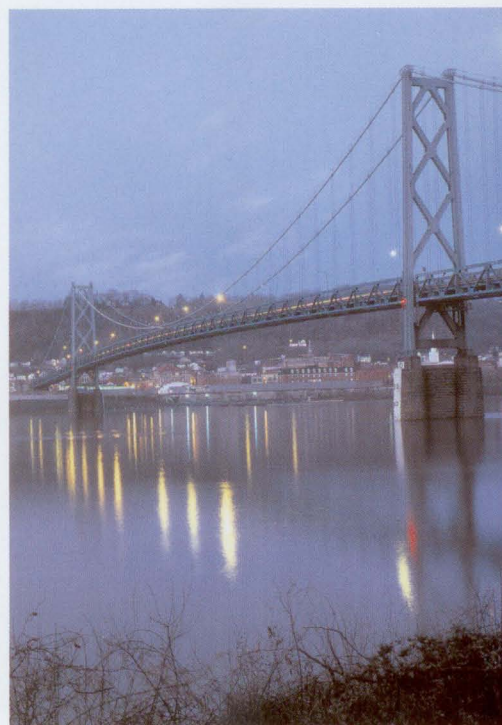
Below left: Side view with appreciable necking

Right: Stress-strain curve



In the assessment evaluation of cable wires against fracture, the applied stress, flaw size and fracture toughness constitute the fracture mechanics triangle. Fracture-based analysis provides a mathematical relationship between these variables, which define a fracture driving force represented by the stress field ahead of a sharp crack. This stress field is characterised by a single leading parameter called the stress intensity factor,  $K_I$ . The fracture resistance, on the other hand, is defined by the critical value of the stress intensity factor. The wire material will sustain a crack without brittle fracture as long as the applied stress intensity factor,  $K_I$ , is below the critical value,  $K_{Ic}$ , which is called fracture toughness. With that rationale, fracture toughness, which is a measure of material resistance to brittle fracture, is an indispensable parameter in the evaluation of cracked wires. To date, however, the fracture toughness of cable wires has not been well defined.

The most favourable conditions for the occurrence of processes of ►



MAYSVILLE SUSPENSION BRIDGE

Hardesty & Hanover provided analysis for full deck replacement for the Maysville Bridge over the Ohio River in 2003.

## Endurance through excellence.

Our goal is to provide the highest level of professional services on every project, *measuring success on client satisfaction.*

Structural • Mechanical • Electrical  
Geotechnical • Seismic • Hydraulics/Scour

For more information about our Long Span Bridge Expertise, please contact our Director of Long Span Bridges, Khaled Mahmoud, PhD, PE

[www.hardesty-hanover.com](http://www.hardesty-hanover.com)

Headquarters, 1501 Broadway, NY, NY 10036  
P: 212-944-1150, F: 212-391-0297

Florida Maryland Michigan  
New Jersey New York Virginia Washington

HARDESTY & HANOVER, LLP  
BRIDGE ENGINEERING





► absorption of hydrogen are found at the crack tip, in the small area of fresh metal surface not covered with a protective oxide film. The underlying principle in the application of fracture mechanics to this case is that when the stress intensity factor at the crack tip is less than a certain threshold value, the crack does not grow. But when the stress intensity factor exceeds the threshold level, the rate of crack growth increases monotonically with increases in the stress intensity factor. The threshold value is a constant that depends on the environment-material system.

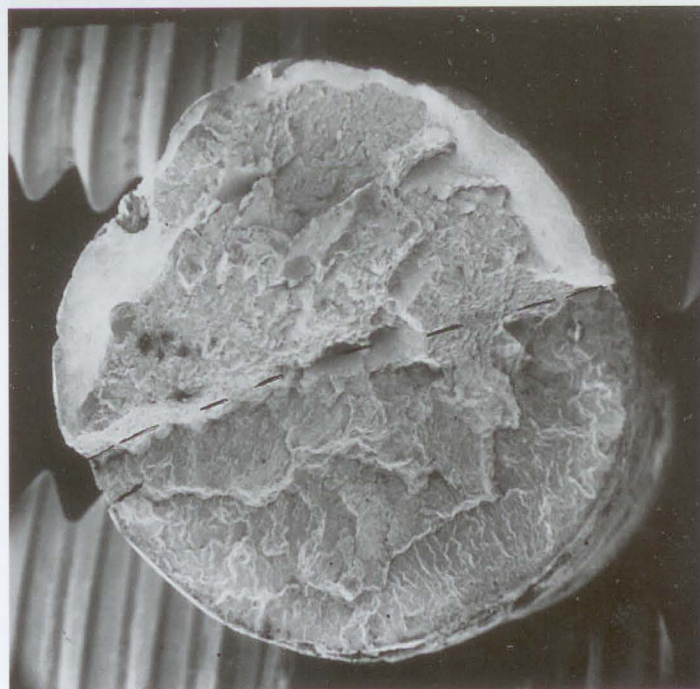
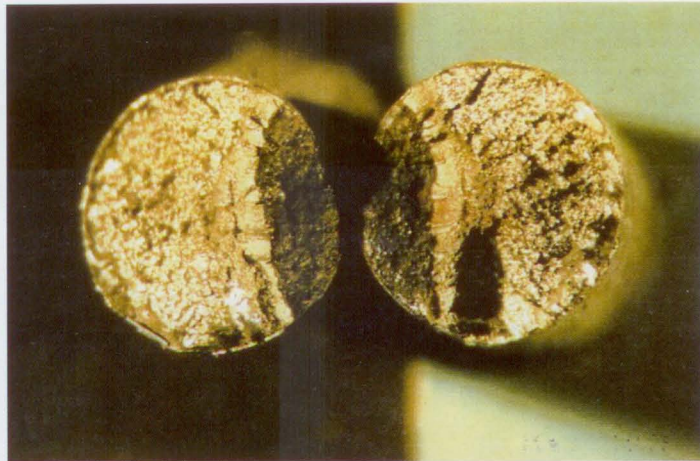
The influence of moisture and hydrogen is most significant in the process of sub-critical crack growth, where the incubation period is always highly dependent on the state of the surface of the smooth specimen and, when there is a notch, on its sharpness. Hydrogen is present in the metal in the atomic state in the form of protons (proton gas). As temperature and external pressure increase, solubility increases. The capability of hydrogen for dissolution and diffusion in metals is significantly retarded by the adsorption of oxygen and the presence of oxide films. The inhibiting effect of oxygen in hydrogen and water is explained by the much greater chemical activity of the oxygen-metal pair than the hydrogen-metal pair. Therefore, a thin oxide film is formed on the fresh surface of metal at the crack tip, protecting the metal from contact with hydrogen. When the oxygen feed stops, the process of reduction of oxygen by hydrogen, or dissolution of the film by water, begins to predominate. Following this mechanism, hydrogen embrittles the high strength material of the wire, decreasing the ductility and overall strength (the greater the concentration of hydrogen, the less the ductility).

Constructing an analytical model for the combined effects of loading and environment is an important milestone in addressing the role of environmental factors in accelerating the crack growth in bridge cable wires. A new model has been developed for the assessment of fracture toughness of deteriorated cable wires. This model determines the mode of wire fracture - stress corrosion or hydrogen embrittlement - through the examination of broken wire surfaces using scanning electron microscopy and the stress-strain curve of tested wire samples. In studying the notch toughness of cable wires, a surface edge-crack subject to tensile stress is considered the prevalent mode of fracture. In this mode, also known as the opening mode, the tensile stress is applied normal to the faces of the crack. To develop the appropriate stress intensity factor and its critical value, fracture toughness, it is necessary to accurately determine the crack geometry. Examination of broken wires indicates that surface cracks undergo a shape change. The crack tends to assume a semicircular front very early in the crack growth process. As the

Above: Mid-Hudson suspension bridge in Highland, New York; the structural safety evaluation of the cables will be carried out using the new methodology

Top right: Semicircular crack front

Right: Straight crack front



crack extends, its front tends to flatten and approaches a straight shape. The new model provides a solution to the stress intensity factor covering the entire range of the crack growth process for axial tension and for the bending stress resulting from straightening the wire. Finally, the fracture toughness of the wire is determined based on the measured crack depth at failure. The model also correlates the strain energy density evaluated from the stress-strain curve of wire samples to the fracture toughness. This latter approach allows the engineer to use the recorded history of wire breaks to establish the pattern of deterioration in the cable wires based on the fracture analysis of data. The estimated values for the fracture toughness are then used to assess the remaining safe life of the bridge cables.

Consultant Hardesty & Hanover has been contracted to apply this new technology to assess the structural safety evaluation for the main cable wires of the Mid-Hudson Suspension Bridge in Highland, New York. It has a total length of about 914m and a main span of 456m, and was opened to traffic in 1930. Each of the two main cables is composed of 6,080 parallel wires. The cable investigation is being carried out under the supervision of William Moreau, chief engineer for the New York State Bridge Authority, which owns and operates the bridge. The project is due to finish by autumn of this year ■

*Khaled Mahmoud is an associate and director of long span bridges at Hardesty & Hanover and an adjunct professor at Columbia University in New York City*

**Bridge**  
design • engineering

Bridge design & engineering (Bd&E) is the only magazine that addresses the bridge industry worldwide. Four times a year Bd&E brings you news and events, project reports, interviews, technical & application features and the latest asset management techniques.

For further information about Bridge design & engineering please contact Hemming Information Services on +44 (0) 20 7973 6681.