INSIDER KNOWLEDGE

Instrumentation and testing of a section of cable based on the ones for the new self-anchored suspension bridge in San Francisco will provide data for a structural health monitoring system being developed. **Lisa Russell** reports

R eplacing a suspension bridge cable is enormously expensive and is not a decision to be taken lightly. Yet it is difficult to establish a full picture of the cable's internal condition, as opening it up for inspection can only reveal a small part of the strands and wires within. Bridge Technology Consulting is the principal investigator for a project aimed at developing structural health monitoring for bridge cables. A section of cable like the one that will be used on the San Francisco-Oakland Bay self-anchored suspension bridge is being fitted with an extensive set of sensors and then subjected to accelerated degradation. BTC president Khaled Mahmoud believes that the results will provide the basis for a monitoring system that can establish ongoing degradation in bridge cables through the use of sensor technologies "so that we have our hands on the pulse of the cable".

The research will use an environmental chamber to mimic the degradation mechanisms that act on real bridge cables while sensor technologies track condition as the cable deteriorates. The experiment will enable the information gathered by the sensors to be compared with the actual physical damage and will provide data for use in BTC's method for the assessment of the remaining strength and service life of main bridge cables.

Corrosion, hydrogen embrittlement, cracking and broken wires can cause significant damage and sometimes even lead to the closure of a bridge, says Mahmoud. Pitting is another cause of damage that is being investigated. The localised corrosion at a particular spot on the wire may lead to crack initiation and could also serve as ports for hydrogen diffusion into the wire interior, causing embrittlement, he says.

The experiment, which is funded by the USA's National Science Foundation, involves instrumentation and testing of a mock-up bridge cable 5.5m long, made up of hundreds of high-strength wires. The cable mock-up will be contained in an environmental chamber and its entire cross-section will be under tension, with a total force of 5,782kN - a level comparable to that on a real suspension bridge cable. All the wires in the cable cross-section will be fully loaded to the same level of service load in real life bridge cable wires, achieving similar conditions, says Mahmoud. "This is necessary to attain full interaction between the load in the wire and the degrading environment. Otherwise, the unloaded wire will not display the forms of degradation, such as cracking or breaking as exist in loaded bridge wires, which could lead to erroneous results," he says. "Without loading in the wire, it would definitely outlive me. But if it is under load and subject to a corrosive environment, then it might not last many years."

The investigation will explore long-term corrosion and degradation effects on today's high grade wires, says Techstar president Steve Brown. He sees the findings as being relevant both for new bridges and those older structures that may need cable replacement in due course. The cable that is being tested is based on the ones being provided by Techstar/Shanghai Pujiang Cable Company for the San Francisco-Oakland Bay self-anchored suspension bridge *(see page 56)*. The investigation is not directly linked to the project, though the idea of including cable sensors has been floated to client Caltrans.

Having every wire under full load will give an insight into the behaviour under the prevalent stresses in a real bridge, says Brown. Wires are becoming stronger, resulting in a reduced cable section. "Under load, these higher-strength steels appear more susceptible to corrosion." They are also more vulnerable to degradation arising from factors such as kinking of the wire during construction. Investigation of these issues is especially important, he believes, as there is talk of steel wires that could reach 2,000MPa, which may further exacerbate the issues of corrosion and degradation.

Mahmoud points out that monitoring of older suspension bridges has only started relatively recently and this makes it harder to have a true picture of their rate of degradation. There have
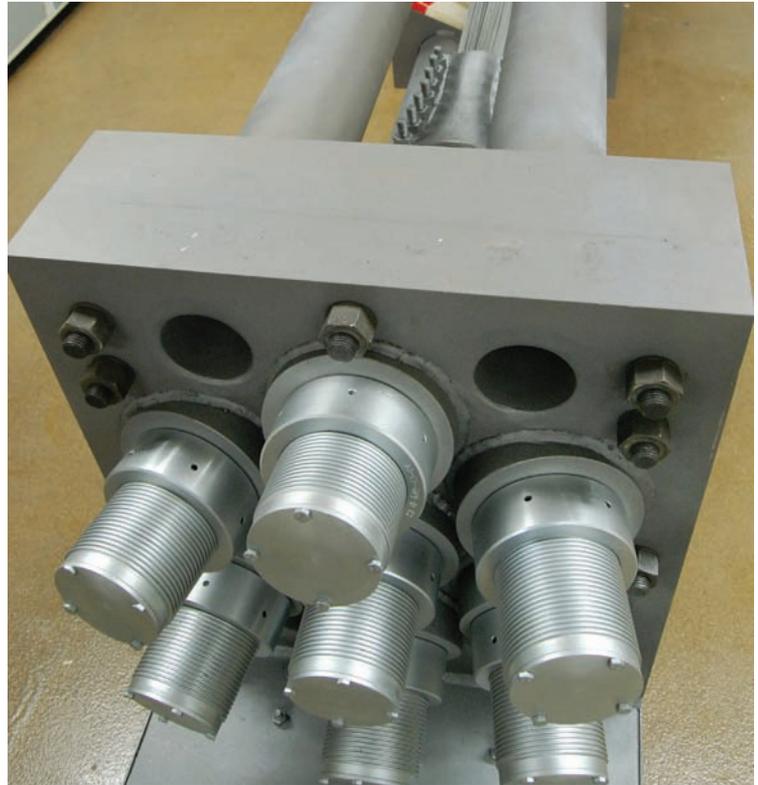
Above & below: Detail of the testing set-up

been cases of wire breaks and degradation in cables aged less than 10 years, which he attributes to a probable combination of many aspects, including inadequate cable and protection systems, an aggressive environment and the presence of salt water.

The research has a series of steps, beginning with construction of the cable section. Instrumentation includes different sensors to measure aspects such as humidity, temperature, corrosion rate and wire breaks. There are also sensors to measure the strain reduction as the cables degrade. The research team has built a corrosion identification device whose working principle is based on detecting corrosion by measuring the magnetic mass of wires constituting the cable. The device will be fitted around the perimeter of the new cable prior to degradation to obtain the initial magnetic properties. It will then be used to keep track of degradation by measurements of the magnetic mass during the experiment.

Once the environmental chamber has been built around it, the cable will be subjected to accelerated degradation, including through the introduction of moisture. It will be subjected to cyclical temperature changes to mimic hot summers and harsh winters.

Wedges being driven into the cable sample

Breaches in the zinc coating will allow moisture to enter and cause the damage. The initial plan is to allow the coating to break down as a result of the induced environmental conditions to mimic zinc depletion on bridge cable wire. Deliberate breaches may also be introduced to ensure the mimicking of certain phenomena such as stress corrosion cracking and wire breaks, says Mahmoud. "In addition to the self weight and temperature-induced loading, bridge cables are also subject to live loads. As such, we have designed the anchor system of the cable mock-up to allow for variation of the load to mimic the effect of live load while the cable is being degraded within the environmental chamber," he adds.

High strength steel wire is on average three to four times stronger in terms of ultimate strength capacity than mild steel, he says, and the strength enables the cable to be kept to a reasonable size despite the tremendous loads applied. However, the high strength is at the expense of the wire's ductility, he says.

Corrosion is not the only thing that matters, he stresses – it is but one of the forms of degradation. Corrosion, embrittlement and all the effects of moisture culminate in a degraded condition, with broken or cracked wires and reduced carrying capacity.

In addition to corrosion, moisture causes the chemical reaction that frees atomic hydrogen, which can penetrate the wire and lead to embrittlement *(Bd&e issue 31)*. The form of rupture in the vast majority of broken wires is embrittlement, he says. There is no significant cross-section loss and the embrittlement is manifested in the ultimate strain capacity, resulting in ultimate strain reduction or strain degradation. Under the influence of hydrogen embrittlement there can be a significant loss in ductility. This is less prevalent in mild steel as its grains are closely attached together and have a stronger inter-atomic bond giving greater protection against hydrogen embrittlement than in high-strength steel.

There is synergy between corrosion and hydrogen embrittlement, and there could be interaction or a combined regime, says Mahmoud. "However, they are two different forms of degradation," he stresses. He would like to test the effectiveness of dehumidification once the project's cable has been saturated with moisture and shows signs of degradation and embrittlement. A breaking load will be applied as a final step to establish the cable failure mechanism and compare it with analytical predictions.
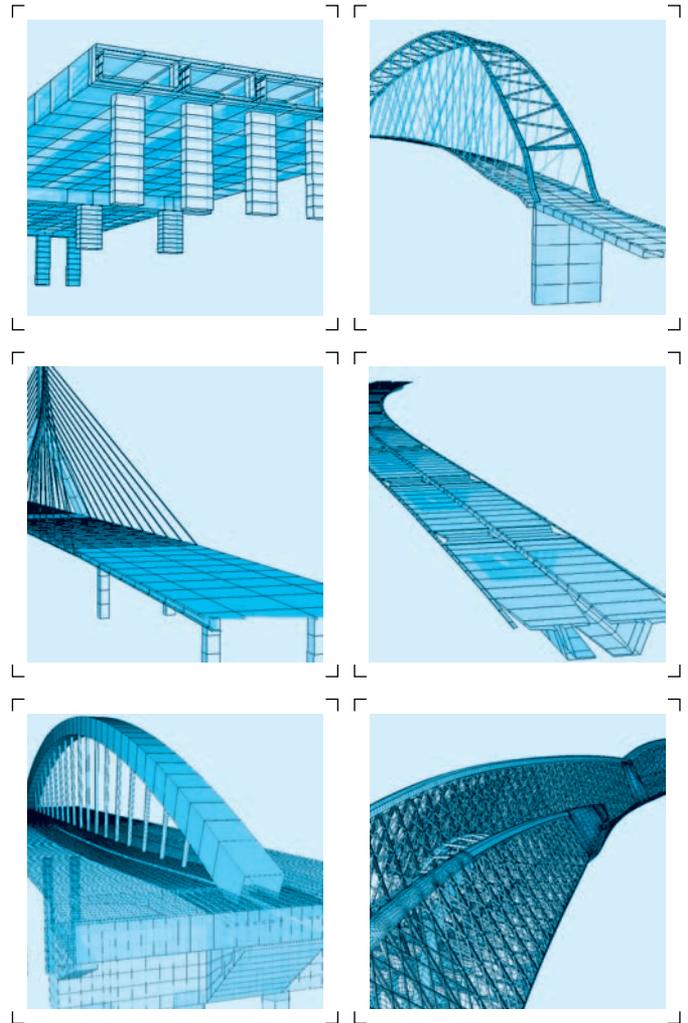
Testing will start shortly and Mahmoud expects it to run for about five or six months. The cable mock-up has been wedged and the next step is sensor instrumentation, followed by building the environmental chamber. Dozens of sensors will be fitted to the test cable. Most are ones that are commercially available, but there is no bias towards a particular sensor. "I'm of the opinion that there is no sensor that fits all sorts of degradation," says Mahmoud. The testing will help establish which types of sensor monitoring could be considered essential for capturing these kinds of degradation activities and remotely reporting back. Resources could then be better deployed when inspecting the cable.

The cable mock-up project has been developed to fit in with the BTC method for the assessment of the remaining strength and service life of main bridge cables. This approach employs random sampling of wires, the principles of fracture mechanics and statistical analysis of wire test results to provide a decision-making tool designed to deliver a more reliable assessment of the remaining cable strength. It uses the cable's history of degradation to forecast the future degraded strength of bridge cables. In addition to providing validation for the performance of various non-destructive techniques, the research will provide verification of the degradation mechanisms encompassed by the BTC method, he says, which is currently being applied on the Bronx-Whitestone Bridge and the Mid-Hudson Bridge in the USA ■