Chapter 7
Ruptures of prestressing cables

Jean-Paul Balayssac, Carmen Andrade, Javier Sanchez Monteiro, and Horst Scheel[1]

1 Definition of the problem

1.1   What is looked for?

The structures involved are **prestressed concrete structures**. The aim is to detect either **failures of prestressing cables (or strands)** or as a **preventive measure to detect corrosion or damages** before failure.

The corrosion of prestressed cables has been the cause of few structural failures with a high impact, since they occurred without any warning. The most famous case if that of the 32-year old small Ynys-y-Gwas bridge in the UK, of segmented concrete post-tensioned construction, which suddenly collapsed in 1985. Due to the lack of safety (or impossibility to assess it), Britain had a moratorium on post-tensioned bridge construction in 1998.

The forensic investigation of the Ynys-y-Gwas bridge collapse [Woodward et al, 1989] confirmed that the collapse was caused by the intrusion of water and

---

[1]Johannes Hugenschmidt and Denys Breysse have also contributed to this section.

J.-P. Balayssac
Université de Toulouse, UPS, INSA, LMDC
(Laboratoire Matériaux et Durabilité des Constructions), France
e-mail: jean-paul.balayssac@insa-toulouse.fr

C. Andrade • J. S. Monteiro
Eduardo Torroja Institute for Construction Science, Madrid, Spain

H. Scheel
Technische Universität Berlin, Institut für Bauingenieurwesen,
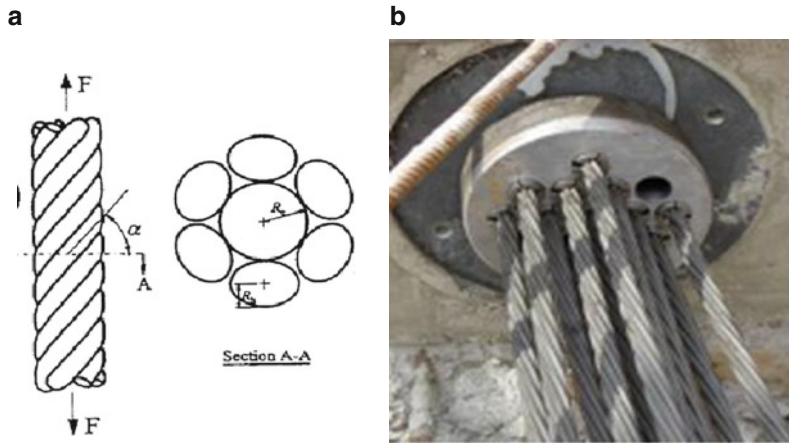Fachgebiet Baustoffe und Baustoffprüfung, Germany

a   **b**

Fig. 7.1 Example of a strand (**a**) and of a cable (**b**) with many strands in the same duct at the anchorage

chlorides at the joints which corroded the internal cables insufficiently protected with cardboard. The bridge gave no visible warning signs of cracking, and as one had no way to inspect the internal cables it was impossible to forecast the accident. Intrusion of contaminants can also occur due to faulty grout, as with Lowes Speedway which suddenly collapsed in Charlotte (North Carolina, USA), on 2000, 20th may, injuring 114 people.

A strand is made up of several wires (usually seven), and the cable is generally made up several strands (Fig. 7.1). Usually the tendon is the whole system composed by both the cable and the duct filled by the grout.

The assessment of the prestressing cables is important to confirm if the design strength of the structure is always available. Field experiments show that most of the prestressed structures that will need maintenance in the future rely on proven techniques with cable systems. These cables are using different design and technology. Prestressed concrete consists in two predominant fabrication or construction categories: pre-tensioned and post-tensioned.

Pre-tensioned systems are generally used within prefabricated concrete beams and in this case the cables are anchored by bond with surrounding concrete. Post-tensioned structures can use only internal tendons (i.e. inside concrete) or both internal and external tendons (i.e. outside concrete) (box girder bridges). Internal tendons consist of many strands surrounded by a metallic or plastic duct. The duct is filled with a grout or with grease. In this case, the cables are difficult to investigate because the depth of concrete cover can reach many decimeter and also due to the presence of the metallic duct. External tendons consist of many strands fully encapsulated within a continuous high density polyethylene duct filled with grout or grease. The advantage of external prestressed tendons is an easier access for inspection and monitoring than internal tendons.

In post-tensioned concrete structures, it has been found many times that the ducts had big voided sections (due for example to bad injection) and were filled

Fig. 7.2 An example of corrosion of strands with broken wires [Chauvin, 2005]

only partially. These voids can be present in some critical areas of the ducts for example in the anchorage areas, where corrosion can be initiated. Indeed, chloride-bearing water can find its way through anchorage inside the ducts and eventually initiate a corrosion mechanism at the anchorage and subsequently of the prestressing steel inside the ducts. In pre-tensioned concrete structures the surface of the concrete can be in contact with corrosive media (de-icing salts or marine environment for bridges for example) and in the case of bad waterproofing, the chlorides can reach and depassivate the prestressing steel.

Many kinds of corrosion can occur, either a general corrosion or a pitting corrosion which leads to a stress corrosion cracking because the steel is under tension. Moreover, sometimes, corrosion reactions lead to the evolution of atomic hydrogen, which can be subsequently absorbed into the steel leading to hydrogen embrittlement of the steel and subsequently to failure. These damages can also be increased by creep and also by fatigue and fretting fatigue. See Fig. 7.2 for an example of corroded and broken wires.

1.2   At what scale?

Three levels of investigation can be distinguished:

Level 1- at the scale of the whole of the structure: for a complete assessment of the structure. This consists of a monitoring of the structure by acoustic emission for example or by vibration analysis. Usually, acoustic emission is able to detect and to localize ruptures of wires. Private companies are able to provide such delivery for long time monitoring of structures. Sometimes if the structure is sensitive, the monitoring can be used as a surveying mean. Regarding the resolution of the localization it depends on the number of sensors and usually it is not very high.

Level 2- at the scale of a part of the structure (a girder, a part of the deck): after a visual discriminative inspection or a monitoring which has permit to define some critical zones. The aim is to localize the failures with a good accuracy. This can be

usually achieved by magnetic technique (remanent magnetic method or magnetic flux leakage). Several special techniques are also described in the literature (electro-magnetic resonance measurement, eddy current …).

Level 3- at the <u>scale of a cable</u>: this can be used to define what kind of damage is involved in the rupture. For example, to check if the duct is correctly filled by the grout or if there is an active corrosion. For an assessment of the grouting quality, radiography or radioscopy can be used which provides an image of the entire tendon. But the size of sounded area remains limited. Moreover for safety reasons (the technique uses radioactive rays) it is more and more difficult to implement it, particularly in the vicinity of habitations. Some studies are now in progress to study the efficiency of Impact Echo for the detection of voids inside the grout.

Any level can't give a complete answer for the diagnosis of a structure. It would be important to provide a global approach which allows a global diagnosis of the structure, first a discrimination of critical zones and then a more accurate sounding of these zones.

1.3   For what purpose?

The assessment of the ability of an existing concrete bridge to function must take into account the condition of the prestressing cables. Many failures of tendons have been observed around the world which demonstrates the importance of this problem. A lack of appropriate data can induce a very expensive and destructive assessment of the cables integrity. But, up to now, no methodology for assessing the integrity of the tendons is available. Generally this consists of fixed-interval inspections made by visual observation of the structural elements. But in most cases the rupture of wire or strands is not visible at the concrete surface. A re-bonding of the broken wires by friction on the grout is usual and so the behavior of the structure may remain almost the same. For example, about the Ynys-y-Gwas in the U.K. [Wood, 2008], it was impossible to see any warnings before the collapse. Indeed, the first visible phenomenon is a bending or shearing cracking which results in important prestressing losses. At this stage a lot of stresses are transmitted to the passive reinforcement and a sudden failure of the structure is possible.

So, without any information from a visual inspection, the choice of areas to implement a reliable assessment of the cable by means of destructive or partially destructive techniques is very difficult. Only non destructive testing methods can be implemented to allow a representative diagnosis of a complete structure. Further, no effective means exist for quantitatively measuring condition of the strand. No methodology for integrating results of such measurements into the strength and serviceability rating computations are available. Ideally, a technique able to inves-tigate prestressed reinforcement in concrete and to generate data regarding residual strength of the reinforcement would permit to reach these objectives.

There is a need for investigating the cable condition e.g. how many wires are broken, or is there an active corrosion? Quantitative information, which must be accurate and reliable are required to be used in a process of re-calculation, in order to place the structure in its life cycle; this point is very important because it's conditioning the reliability of the assessment.

Two different approaches can be considered:

– the cable investigation in order to detect a failure and then to go far in the diagnosis: what is the cable condition particularly how many wires are broken, is there an active corrosion which can rapidly induce an other failure?
– the investigation of the cable condition (even if no failure is suspected) in order to quantify the probability of development of corrosion or to detect the presence of un-grouted areas where corrosion can be initiated. This approach could be rather considered as preventive.

2   Description of the techniques

For on site non destructive evaluation of rupture of cables, three common techniques can be considered. These are:

• Radiography,
• Magnetic methods: Remanent magnetism method "RMM" or magnetic flux leakage "MFL",
• Acoustic emission.

For these techniques a presentation is made for detailing their principle, their limits and example(s) of application, including usual combinations not applied for improving the detection of failures, but for a better implementation. For example, ground penetrating radar for the localization of the cables and impact echo for a detection of voids in the duct can be efficiently used. Sometimes, an endoscope is introduced just behind the anchorages to assess the integrity of the cables (corrosion can be detected for example) [Poston and West, 2004]. But these observations are limited to the vicinity of anchorages.

Other techniques are in a development phase [Laguerre, 2003], [Wichmann et al., 2003] but, up to now, they are only used on laboratory applications, considered as special techniques. However, two types of special techniques will be briefly described at §2.4:

• the Electromagnetic Resonance Measurement (ERM) developed by Holst and Wichmann [Wichmann et al, 2003], [Holst et al, 2007], since it has been already tested on full scale models,
• the electrochemical techniques, that could be useful for the characterization of cable corrosion.
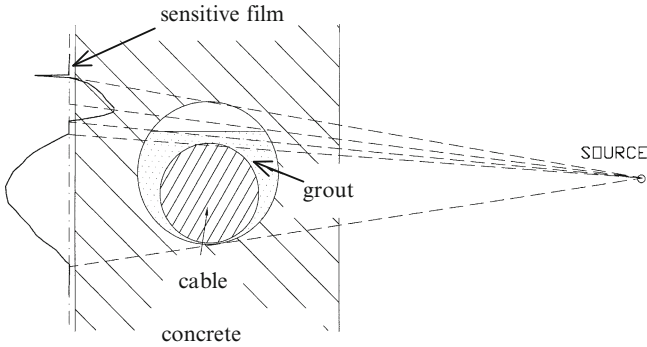
Fig. 7.3 Principle of radiography

Fig. 7.4 Example of radiogram – sounding of an internal tendon [AFGC-B7, 2005]

2.1 Radiography

2.1.1 Principle

In radiography, the radiation source is either X-rays or gamma rays. Gamma rays or X-rays are emitted by an artificial source (Cobalt 60 or Iridium 192). In the case of X-rays, accelerators are used to obtain higher energy. It's a technique by transmission and the radiation attenuation through the material is measured with a sensitive film located on the opposite face to the one where the source is located (Fig. 7.3).

The optical density related to the grey levels of the sensitive film is analyzed. The quality of the images is generally good because the attenuating characteristics of steel, concrete, and air differ greatly (Fig. 7.4).

Field applications of radiography include the detection of reinforcement, voids, and cracks, the quality of grouted post-tensioned tendons and the failure of cables. Radioscopy is a different form of radiography in which the transmitted radiation is converted into visible light and recorded by a video camera. Radioscopy has been used in France for the detection of grouting defects.

The radiographic techniques can provide very useful information because of their ability to observe cross-sectional images of the object. They are applicable for every kind of prestressed concrete structures. However, these methods currently pose the problem of safety and other limitations. With further advancements in portable radiography equipment for field applications, such techniques could be more widely used. In particular, safety increasing, and imaging speed advances to permit practical scanning rates should greatly improve the technique.

Classically, industrial radiography is able to observe:

- the presence of cavities inside the concrete
- the presence of grout inside the prestressing ducts and also its defects
- the position of tendons
- the position of the reinforcement and the diameter of the rebars
- the discontinuities of the ducts
- the broken wires or cables in some cases
- etc.

2.1.2   Limitations of the technique

- *Global limitations:*

  - Like it's a technique by transmission, two faces of the structure must be accessible
  - Depth limitation: 60 cm for gamma rays but 120 cm can be reached with X-rays
  - Only small surfaces can be sounded due to the limitation of the surface of sensitive film
  - Steel bars (cables or reinforcement bars) can mask the target
  - Important weight of the common radiation sources which doesn't enable the investigation of all the parts of a structure.
  - Like the technique is hazardous, security area is required around the structure. Sometimes it's impossible
  - The implementation of the technique is expensive if very large areas need to be sounded. For this reason radiography is sometimes relegated to use only in specific conditions [Poston and West, 2004].

- *Limitations for the detection of broken wires:*

  Besides the above limitations, its low resolution for the detection of damages on the cables is the main disadvantage of the technique: the width of the fracture must be important enough to be detected. Moreover it is linked to the depth limitation.

Fig. 7.5 Implementation of the technique at the intrados of a bridge deck (on the left) and a source of Iridium (on the right) – LPC France

2.1.3   Application

Field applications are currently made for grouting defects investigation, but also, in some cases, for the detection of broken wires [AFGC-B7, 2005], [Dérobert et al, 2002], [Ciolko and Tabatabai, 1999]. For example, in France, radiography (and also radioscopy) is usually implemented (Fig. 7.5) by means of gamma and also X-rays (Scorpion II, Laboratoire des Ponts et Chaussées, in France) [Dufay et al, 1985]. The methodology for the implementation of the technique on reinforced and pre-stressed structures is defined in a standard [NF A 09-202].

2.1.4   Combinations with other NDT methods

- Usual: radar for a fast localisation of the ducts. It's important if the plans of the structure are not available.
- Unusual: impact echo for a fast detection of voids in the ducts [Poston and West, 2004].

2.2   *Magnetic methods*

2.2.1   Principle [Scheel and Hillemeier, 2003]

The magnetic field resulting from a magnetized tendon or a magnetized steel wire is comparable to the magnetic field of a bar magnet. In the vicinity of a fracture a magnetic dipole-distribution is formed and, accordingly, a magnetic leakage field in

Fig. 7.6a Transverse
component of the magnetic
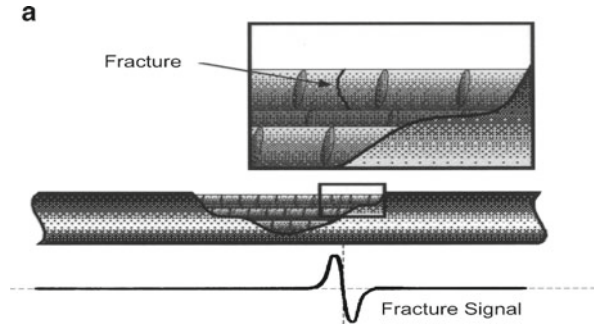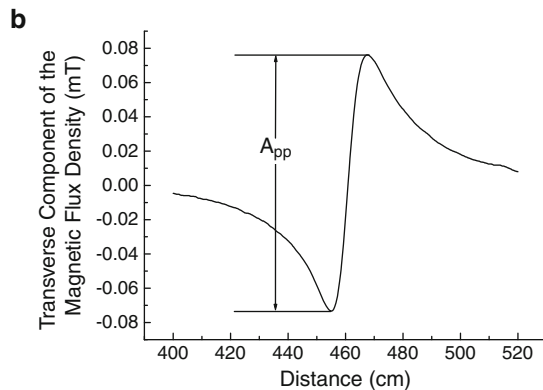flux leakage measured above
a cable fracture

Fig. 7.6b The peak-peak-
amplitude (A_{pp}) of the
transverse component
as a measure of the strength
of the leakage field

the surrounding region. The transverse component of the magnetic flux density, measured at the concrete surface is shown in Fig. 7.6a. The characteristic leakage field allows detecting fractures of prestressing steel wires (Fig. 7.6b).

Two methods are presented in the literature, the Magnetic Flux leakage (MFL) and the Remanent Magnetism Method (RMM), but their physical principle is the same. In practice, these methods consist of applying a steady-state magnetic field to the cable and so the use of a scanning magnetic flux sensor allows detecting the changes in the applied field caused by the ruptures or the cracks.

In order to draw unequivocal conclusions from the magnetic flux density measured at the concrete surface to potential fractures, the external magnetization of the prestressing steel has to generate a magnetic state where all irreversible magnetization processes in the prestressing steel are completed. This is necessary in order to erase the unknown magnetic history of the steel. Without this magnetization the measured magnetic signals could be caused by various former unknown magnetization processes (e.g. transport by lifting magnets). By this way, a homogeneous magnetization of the cables is achieved.

The magnetization of the cables is performed from the concrete surface with an electromagnet. A remanent magnetization of the cables is achieved up to a concrete cover of 30 cm. It is ineffective to magnetize the cables before they are installed, in

order to avoid pre-magnetization because the magnetization will be destroyed partially and locally by the mechanical impacts during the construction process. This might produce signals similar to fracture signals. Demagnetization in the region of a fracture will disturb a fracture signal. The magnetized cable has a magnetic field similar to that of a bar magnet. Fractures of a single prestressing wire within a bundle of wires inside the metal sheathing are detectable by characteristic leakage fields. Figure 7.6b shows the transverse component (relative to the direction of the steel wires) of the remanent magnetic flux density measured at the concrete surface. At the location of a fracture the measurement curve of the transverse component shows a reversing polarity. The peak-peak-amplitude (A_{pp}) of the transverse component of the leakage field is used to measure the strength of a fracture signal (Fig. 7.6b).

2.2.2   Influences on the measurement

Various influences have to be considered in order to locate the position of steel fractures in remanent magnetized tendons and to evaluate the extent of damage:

- concrete cover: the total magnetization of cable is possible up to 30 cm depth,
- cross-sectional area of the prestressing steel wires,
- number of prestressing steel wires in the tendon,
- number of single wires that are broken in the cross-sectional area where the signal occurs,
- bonding between the prestressing steel wires and the grouting mortar (fracture width),
- interfering signals caused by other ferromagnetic components, especially mild reinforcement,
- magnetic and magneto-elastic material properties of the type of prestressing steel.

The peak-peak-amplitude of the transverse component of the leakage field for a certain cable depends on:

- the number of single wires that are broken in the cross-sectional area where the signal occurs,
- the concrete cover: the peak-peak-amplitude decreases when the concrete cover increases and increases when the number of single broken wires increases,
- the fracture width (distance between the fracture surfaces): the peak-peak-amplitude increases when the fracture width increases (Fig. 7.7),
- the degree of prestressing: the peak-peak-amplitude increases or decreases depending on the type of steel with the increase of tensile stress,
- the presence of the reinforcement in case of a high reinforcement ratio. If the reinforcement ratio is usual, while the magnetization of prestressing steel can be maximized by the chosen magnetization procedure up to remanence (the maximum residual magnetization), the magnetization of the mild reinforcement decreases to small values [Scheel and Hillemeier, 1997]. Specific procedures for data processing can also be used for removing the part of the signal induced by the reinforcement [Sawade, 2007].

Fig. 7.7 Relative peak-peak-amplitude of the transverse component of the leakage field as a function of the fracture width for different concrete covers
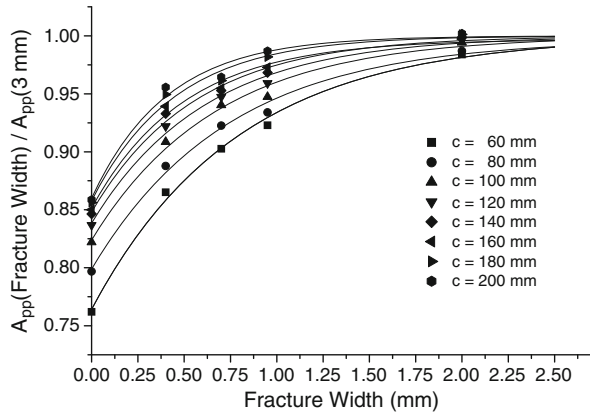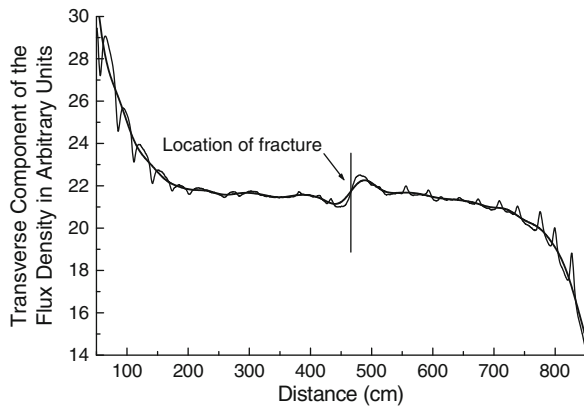

Fig. 7.8 Effect of FFT filter smoothing

The interfering signals caused by the mild reinforcement and other ferromagnetic components are greatly reduced by the applied magnetization procedure; but they are not completely eliminated. In order to reduce these signals and to distinguish them from fracture signals, the following data processing can be applied:

- Simple addition of two measurement data arrays:
  Two arrays with the magnetic flux density data of the system in different magnetic states, in which the residual magnetizations of the mild reinforcement have different signs, but not the residual magnetizations of the prestressing steel wires, are added. The signals caused by all types of mild reinforcement decrease, whereas the signals caused by the prestressing steel increase.
- Fourier Transformation filter smoothing (Fig. 7.8):
  The signals with a small width compared to the width of a fracture signal are filtered out. FT filter smoothing suppresses signals caused by transverse reinforcement (e.g. by stirrups), if their distances do not vary too much. It also filters the signals of ferromagnetic components with a small width compared to
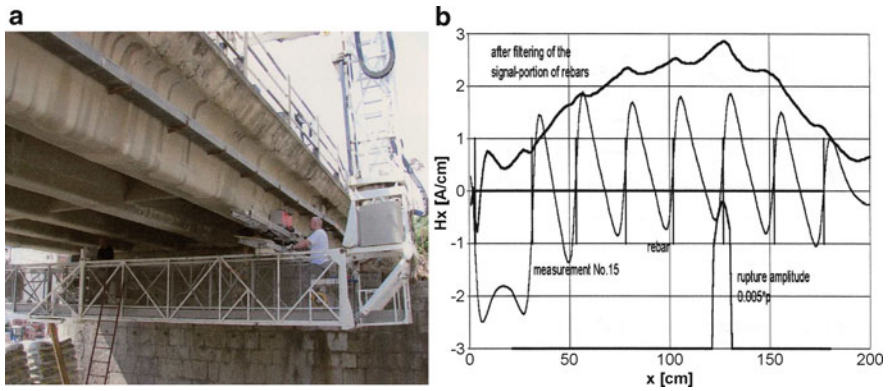
Fig. 7.9 Application of Magnetic Flux Leakage technique for a girder inspection

the width of the fracture signal, e.g. nails, binding wires etc. Noise with a frequency greater than 5 Hz (depending on the measurement speed) is also filtered out. Fig. 7.8 shows a measurement curve and the resulting FFT filter smoothed curve: the measurement curve shows small peaks caused by the residual magnetization of stirrups. The smoothed curve shows the significant fracture signal while the stirrup peaks are filtered out.

- Deconvolution of the (smoothed) curve with fracture signals.
- Calculation of the cross correlation function of the (smoothed) curve and fracture signals.

2.2.3   Application

Several publications upon laboratory validations [Scheel and Hillemeier, 2003], [Makars and Desnoyers, 2001], [Altschuler and Pignotti, 1995] are available. Concerning field applications, Scheel and Hillemeier have implemented the technique on the vertical surfaces of prestressed beams, on the upper surface of a bridge deck [Hillemeier and Scheel, 2004] and on parking structures [Scheel and Hillemeier, 2003]. Krause and colleagues have successfully implemented the technique for the detection of broken wires inside a bridge deck [Krause et al, 2000].

Fig. 7.9a presents an example of application on a girder of a highway bridge with one broken single-rod tendon (which was in a metallic duct) [Sawade, 2007]. Fig. 7.9b presents the different signals obtained along a 2 m long profile. First it is possible to see rough signal which was obtained by the measurement (called measurement N°15 on the picture). The rapid changes of the field amplitude are linked to influence of the reinforcing bars. After filtering the signal portion induced by the reinforcing bars (see 2.2.2.), the upper signal is obtained. The position of the rupture clearly appears on the diagram which plots the variation of the rupture signal at about 125 cm (bottom curve).

Fig. 7.10 Wire break: typical response of a sensor (time domain)
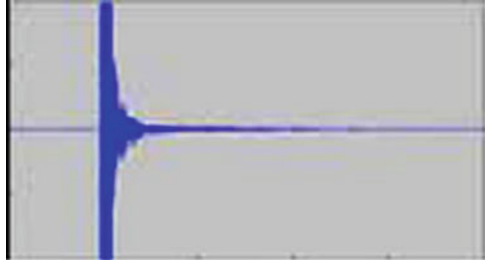
2.2.4   Combinations with other NDT methods

- Usual: radar can be used for the localisation of the cables and a more efficient magnetisation of the steel.
- Unusual: impact echo for a fast and non expensive detection of voids in the ducts. Indeed, in these areas corrosion can process and so the probability of broken wires is higher.

2.3   *Acoustic Emission*

2.3.1   Principle

When an acoustic emission occurs at a source within a material due to inelastic deformation or to cracking it generates a stress wave which can be detected by an adapted receiver. The signal recorded by the receiver can be affected by the nature of the source, the geometry of the tested specimen and the characteristics of the receiver. The sensors used are broad-band or resonant piezo-electric accelerometers which convert the surface displacement into an electric signal. Acoustic emission testing is a "passive" monitoring method in which the detection system waits for the occurrence and capture of stress wave emissions associated with cracking, corrosion, or wire breaks. By contrast, classical flaw detection methods, such as ultrasonics, are considered "active" because a stress wave is sent into the test object to identify the presence of defects.

In the case of a prestressed cable the failure provides a sudden release of energy. This energy can be dissipated by means of acoustic waves through the surrounding media. The signals generated by wire failures must be detected above general noise levels and distinguished from events which are not of interest. By using several characteristics of the acoustic events including frequency spectrum it is possible to classify wire breaks and to reject environmental noise. Furthermore to assess the implication of each event on the structure it is important to locate the source of each emission. By analyzing the time taken by the energy wave caused by the failure as it travels through the concrete up to the different sensors, it is possible to calculate the location of the broken wire. Fig. 7.10 shows a typical acoustic response of wire

break (in a strand of an internal tendon in this case) monitored by a sensor 10 m away [De Wit, 2004].

The quality of the structure assessment is linked to the importance of the monitoring. More important is the number of inspection points better is the assessment. In many applications the acoustic data are transmitted via the Internet for processing and analysis.

Moreover some studies are currently implemented for testing the sensitivity of acoustic emission to the detection of corrosion development. It seems that the energy released by corrosion development is not very important versus all the environmental noises.

2.3.2   Limitations

– The breaking phenomenon is very short in time so it's necessary to monitor continuously during a long time (sometimes several years). Moreover the data acquisition must be done with a sufficiently high sampling rate.
– The technique does not provide any information on failures that occurred before its implementation
– Accuracy of the localisation: it depends on the number of sensors. By mean of multiplexing, usually it is possible to acquire on 32 channels, but it is not a general limitation [De Wit, 2004].

First example

It concerns the monitoring of a bridge in Switzerland. The monitoring is done by the company ADVITAM (SOUNDPRINT System) in collaboration with the Institute of Structural Engineering (ETH) in Zurich [Flicker and Vogel, 2007], [Hovhanessian, 2005]. The bridge is prestressed by internal tendons (63 cables with 12 wires of 7 mm diameter - system Freyssinet P50). 11 natural failures of the wires are monitored and localized with accuracy between 10 and 60 cm. In order to test the reliability of the technique, artificial failures are generated with an accelerated corrosion process. These artificial ruptures are also detected and localized (Fig. 7.11) with accuracy between 20 and 50 cm. The results confirm that the detection quality of the ruptures can be disabled by a bad grouting of the duct. Indeed, in this case, the high attenuation of the signal may disturb the data processing [Hovhanessian and Laurent, 2005].

Second example

It concerns a study realized both on laboratory beams and bridges in Japan [Yuyama et al, 2007]. AE is tested for the detection of wire failures due to corrosion. On a laboratory beam (Fig. 7.12) the failure is introduced by artificial corrosion (by applying anodic current) and the influence of grouting conditions is tested. The results show that the amplitude of the waves exceeds 100 dB and the source location is possible for the failures of unbonded and partially grouted cables. When the cable is fully grouted even if the detection is possible the location is not easily performed. Nevertheless, about 82% of the wire breaks are detected. Different resonant sensors
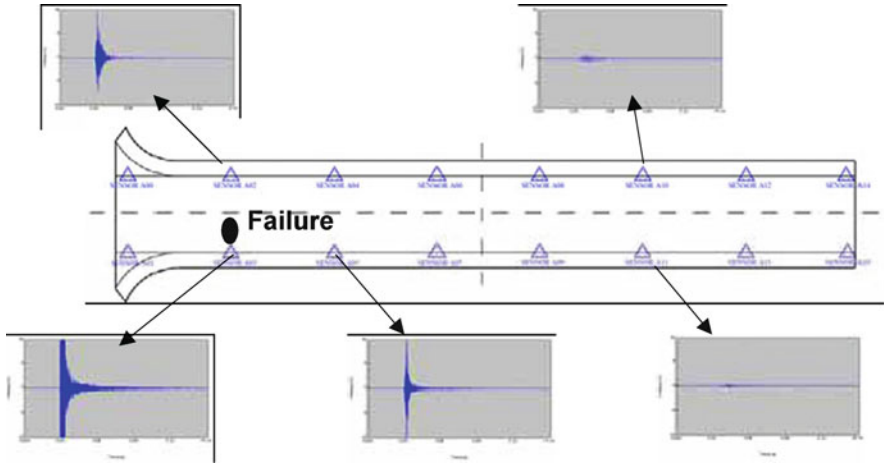
Fig. 7.11 Artificial failure of a wire: response of different sensors (after [Hovhanessian, 2005])
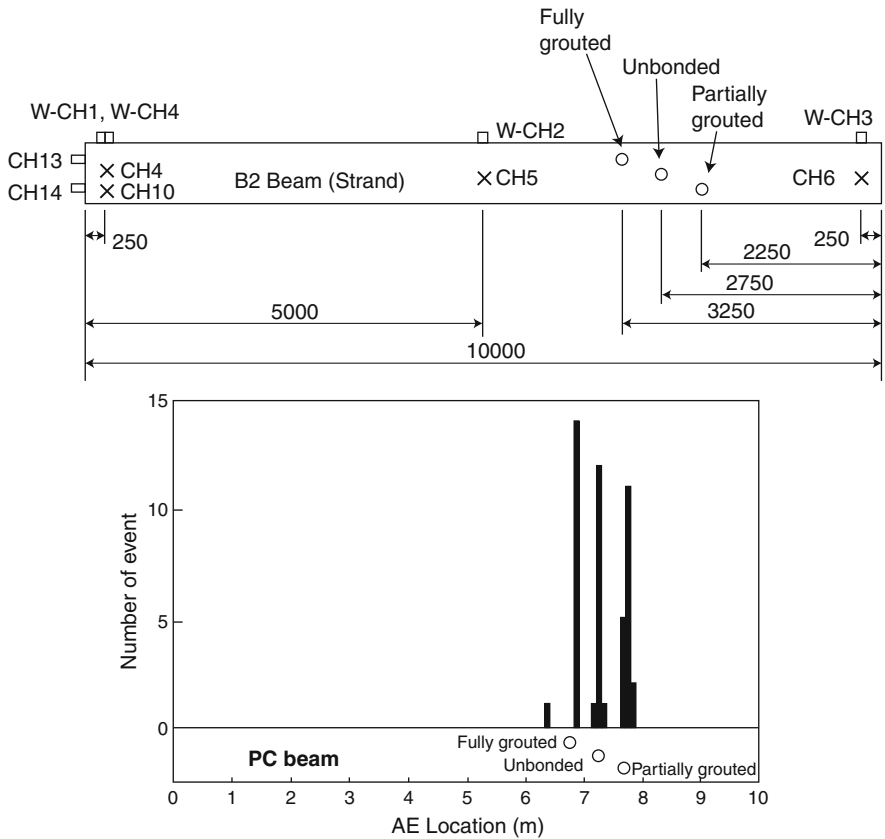

Fig. 7.12 Laboratory beam and location of wire failures (after [Yuyama et al, 2007]

are tested (30 kHz, 60 kHz and 150 kHz) and it is clearly demonstrated that the sensitivity increases as the resonant frequency of the sensor decreases. The amplitudes detected by 30 kHz sensors are very high (over 100 dB), those by 60 kHz are high (60-100 dB) and those by 150 kHz are low (50-80 dB).

For the field tests two bridges (a box girder beam and a T-shaped beam) are tested. The activity due to wire breaks is compared to those resulting from traffic noises. Even if traffic noise is a major AE source, the results show that the amplitudes are higher than 90 dB, continuing for 1-2 s. The ratio of wire failures detected under traffic conditions are about 80% for one bridge and 90% for the other one. The location of the source is also possible on the bridges with an error less than 8%. Other tests show that the attenuation of the waves during propagation is about 30 dB while it travels about 7 m (using a 60 kHz resonant sensor).

A literature review provides other examples of detection of cable ruptures on bridges [De Wit, 2004], on pipes [Travers, 1997] and on nuclear containments [Graves and Tabatabai, 1998].

2.3.3   Combinations with other NDT methods

Radar can be used for a best localisation of tendons but it is not necessary for the implementation of the technique. Nevertheless, it could be used if a destructive assessment is done after a localisation of rupture.

2.4   Special techniques

2.4.1   Electrochemical techniques

Description

Electrochemical techniques are largely used for the characterization of reinforced concrete corrosion [Andrade et al., 1978&2002]. Both description and implementation of these techniques are detailed into RILEM and ASTM recommendations [ASTM C876-91], [RILEM, 2000&2003&2004]. The main electrochemical techniques for measuring corrosion are:

- The **Corrosion Potential**, E_{corr}, which informs on the state of the metallic surface with respect to the surrounding electrolyte. If the steel is corroding with the production of oxides, the E_{corr} is very negative and if the steel surface is covered by a passive oxide film the E_{corr} is less cathodic or even in the positive range with respect to the saturated calomel electrode (SCE).
- The **concrete Resistivity** (R_e) which indicates the porosity of concrete and the degree of water saturation of concrete pores. Values bellow 50 Ωm indicates pore saturated concrete and values above 500 Ωm indicate very dense or dry concrete. The Re needs to be referred to a particular volume or regular geometry.

Fig. 7.13 "Barrios de Luna" Bridge

- The R_p (polarization resistance) technique which enables the calculation of the **corrosion rate**, I_{corr} in μA/cm^2 or the V_{corr} in mm/year.

In a reinforced concrete structure the measurement informs on the state of the reinforcement closer to the placement of the electrodes, so only the first layer of bars can be measured. However, in the case of post-tensioned elements in which a layer of non prestressed reinforcement is placed between the concrete surface and the ducts, the measurement of the prestressing cable is shielded by this intermediate layer, which in addition is usually electrically connected to the ducts. The only way to monitor the cables is to open a window in the concrete and to put the counter electrode directly on the grout surrounding the cables. In the following sections two examples are presented, a first one on cables of a suspended bridge and a second one on cables in a prestressed concrete bridge.

Examples of application

a) Example 1: measurement in tendons of a suspended bridge (Barrios de Luna Bridge)

The bridge was built in 1983; it is a cable-strayed bridge with three spans. The main span is 440 meter long (Fig. 7.13). The bridge is suspended by means of 228 tendons. Each cable has some high strength steel cable of 1.5 cm diameter. The measurement was made by removing the plastic duct and placing the corrosion rate meter directly on the grout (see Fig. 7.14c).

Once it is achieved an electrical connectivity, it is possible to measure different electrical and electrochemical parameters: resistivity (Fig. 7.14a), potential (Fig. 7.14b) and corrosion rate (Fig. 7.14c). All these parameters let us to evaluate the service life of the bridge.

Fig. 7.15 and Fig. 7.16 show the potential and corrosion rate values of different tendons. Assuming that the process is that of generalized corrosion and that the standards used for the assessment of reinforced concrete corrosion are relevant in
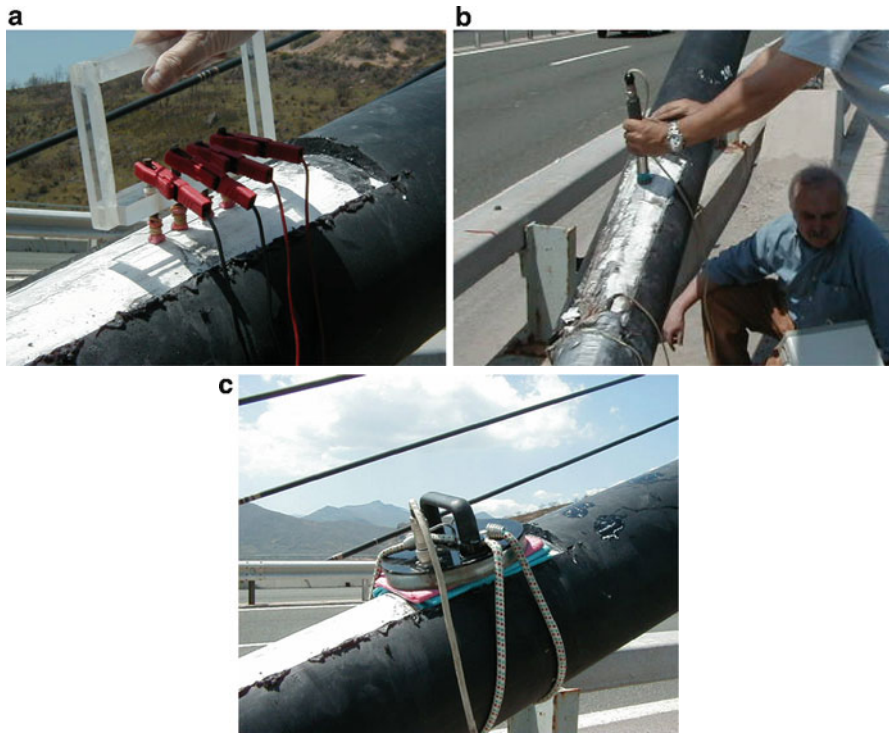
Fig. 7.14 Electrical and electrochemical measurements. (**a**) Resistivity measurement, (**b**) Electrochemical potential (**c**) Corrosion rate
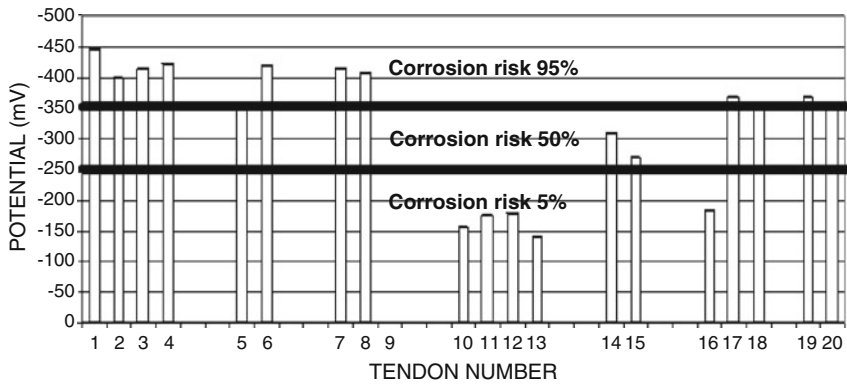

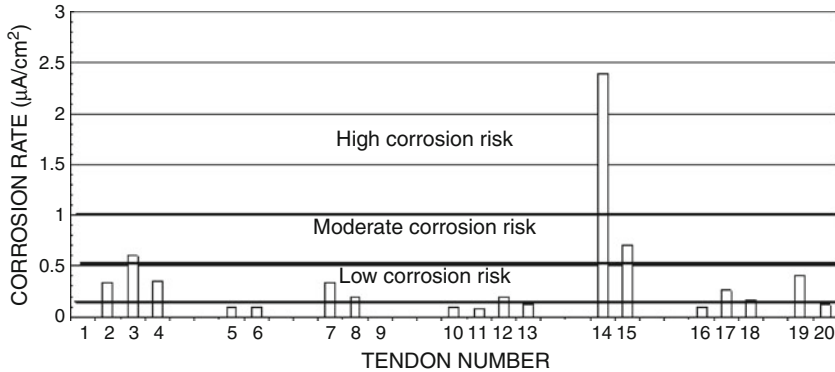**Fig. 7.15** Electrochemical potential of tendons

Fig. 7.16 Corrosion rate of tendons

this case, it is possible to distinguish three levels of corrosion according to electro-chemical potential. And according to corrosion rate measurements it is possible to quantify this risk of deterioration. All these data are necessary to evaluate the residual life of these components.

A lot of values of the potential registered were in the range "moderate to high corrosion risk" (i.e. more than 50%) following ASTM standard. The potential readings are only qualitative and they serve to indicate that the tendons are in a situation where the corrosion is likely to grow.

The quantification is made through the corrosion rate (Fig. 7.16). It has been detected that several points show values of the corrosion rate higher than $0.1 \mu A/cm^2$.

b) Example 2: Measurement in post-tensionned elements

This example concerns a bridge built in 1992 and formed by five spans of 48, 60, 100, 60 and 48 meters. It has a composite section (steel – concrete) which is variable in height and width through the five spans. Over supports, negative bending moment is supported, both by a strong lower plate and seven stiffeners, and a passive and active reinforcement and several prestressing tendons.

When concreting, a change in the water table level of the well, used for concreting, allowed the sea water to penetrate into the water well, and finally the amount of chlorides in the concrete was around 7 times higher that the maximum allowed by standards (~0,4% in weight of cement). Thus, the corrosion in the concrete deck was detected since construction.

During eight years the bridge was continuously monitored in order to know the corrosion rate with the aid of a portable corrosion rate meter with modulated confinement of the current (Fig. 7.17). The results obtained in two sections of the deck are represented in the form of a distribution (Fig. 7.18).

The connection was done on the passive reinforcement as it was verified that it was electrically connected to the tendons. Therefore it was not necessary to make direct connection to the ducts. In addition, as the chlorides were added in the mix,

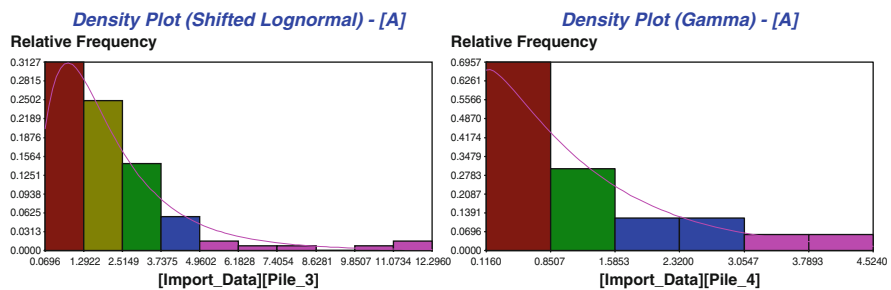**Fig. 7.17** Corrosion rate measured in-situ

Fig. 7.18 Distributions of measured corrosion rate in sections 2 and 3

the corrosion of the passive reinforcement was the same than that of the tendons. This was verified in one case, where direct measurement on the grout was made after performing a window in the duct (Fig. 7.17).

The cover of the duct was removed in several places in order to verify the loss in cross section and directly observe the type of corrosion.

The results obtained showed that the corrosion was in general not too high (current density about 0.2 µA/cm^2) except in one of the sections were the values were higher, reaching sometimes values of 0.5 µA/cm². The conclusions obtained were that the corrosion was not low in three sections of the bridge and moderate in one. The expected life of the tendons was calculated from around 15 to 40 years.

However the failure risk would depend on whether stress corrosion cracking (SCC) develops or not. It is not known at present how to predict the occurrence or not of SCC. SCC would be one of the worst scenarios for the prediction. When it occurs, the failure is much quicker than when produced by normal corrosion.

2.4.2 Electromagnetic Resonance RF-Measurement (ERM)

The technique uses the electromagnetic resonance of the prestressing steel to detect and localize steel fractures and flaws in prestressing cables. The principle of the method is to consider the prestressing cable itself as a resonator located in a material
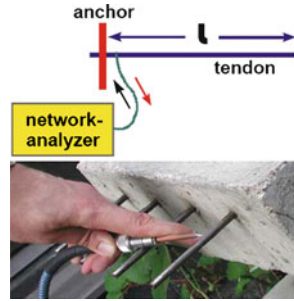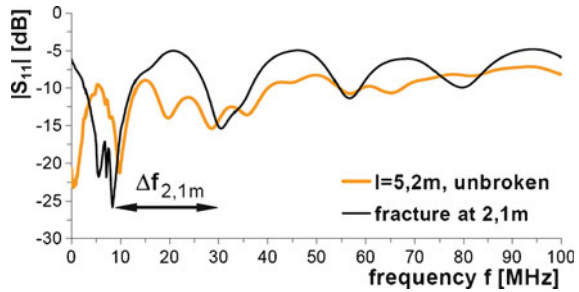
Fig. 7.19 Principle of ERM measurement

Fig. 7.20 Reflection parameter S11 versus frequency f for a 5.2 m long strand in air with and without fracture

with electromagnetic losses (concrete). An electromagnetic wave of variable frequency is coupled to the end of the cable (Fig. 7.19) and the reflection coefficient is S11 is scanned over a large spectrum (from low to high frequencies) by mean of a vector network analyser. The resonance frequencies are recorded and the spacing between two adjacent resonance frequencies Δf (Fig. 7.20) is inverse in proportion to the length l of the tendon, from the source and up to the fracture, and also depends on the dielectric permittivity of the surrounding material ε_r as it is shown in the following equation [Holst et al., 2008].

$$ l = \frac{c_0}{2 \cdot \Delta f \cdot \sqrt{\varepsilon_r}} \quad \text{with } c_0 : \text{vacuum speed of light} $$

One of the difficulties of the technique is to evaluate the permittivity of the surrounding medium. If it is unknown, the distance to the fracture can be determined by comparing the ratio of the measured spacings on the broken wire with the ones of an unbroken wire. The possible limits of the methods are:

- the presence of voids (filled with air or with a salt solution) in the grout which can induce a important change of the dielectric permittivity,
- the contact between the cable and the metallic duct, and in this case the duct is investigated and not the cable.

2.5   Calibration aspects

A calibration is not necessary in all the cases. If the aim of the sounding is only limited to the detection of failures on the cables and not to the evaluation of the number of broken wires, some of the techniques are able to provide such information with rather good reliability. For instance, magnetic technique has proved efficiency for detecting broken wires and moreover, for this technique, sensitivity studies realized in laboratory conditions [Scheel and Hillemeier, 2003] can be used for a calibration procedure on site.

On the other hand, sometimes, a full diagnosis of the whole tendon can be required in order to provide reliable information for a re-calculation of the structure. In this case, information like the number of broken wires, the condition of the wires (for instance is there a corrosion activity) are necessary to be provided to the engineers.

Moreover, for a prognosis of the evolution of the cable condition, another kind of information can be required like, the quality of the grout, the activity degree of the corrosion process, the presence of chlorides and so on. In this case a relative calibration could be helpful, because up to now it remains very difficult to provide data regarding these different points by non intrusive means. Thus, the only available mean to achieve this calibration consists on making a window through the structure, up to the cable. As the depth of the cable is usually at least 20 or 30 cm (more in some cases) the window is very disabling for the integrity of the structure.

2.6   Evaluation and comparison of the techniques

Only radiography, magnetic and acoustic emission are compared. The evaluation is presented in the following Table 7.1 regarding several characteristics [Ciolko and Tabatabai, 1999]. For a given characteristic each of the three techniques is ranked (with A > B > C). A mark "A" doesn't systematically mean that the technique is very good and on the other hand "C" is not a depreciation of the technique. These marks have to be rather considered like a relative classification of the three techniques.

3   What can be done for a better assessment? Combination possibilities

For a recalculation process what is important is to detect and to localize the ruptures or the damages and if possible to quantify the number of broken wires. Up to now, to be accurate and reliable, the answer to this question requires a windowing in the structure so as to observe the cable. But this process is heavy and can alter the integrity of the structure. The combination of techniques could be used so as to optimize the interventions and to decrease the windowing operations. Radiography which is an imaging technique, usually provides relevant information about the whole tendon

Table 7.1 Comparison of the techniques (R = radiography, M = magnetic techniques, AE = acoustic emission, IE = impact echo)

Characteristics	Details	R	M	AE
Applications	Pre-tensioned structures	A	A	B[2]
	Post-tensioned structures with metallic ducts	A	A[3]	A
	Post-tensioned structures with plastic ducts	A	A	A
Ability	Detection of cable or wire failures	B	A	A
	Number of broken wires	C	B	C
	Localisation of failures	C	B	A
	Detection of wire damage	C	B	C
	Detection of corrosion	C	C	C
Operational characteristics	Contact/Surface Coupling	A	A	C
	Need of continuous monitoring[4]	A	A	C
Device details	Equipment Weight	C	B	A
	Sensor Weight	C	B	A
Efficiency	Number of readings (tests) required for a given surface	C	B	C
	Time expended for data gathering for a given surface	C	A	C
	Interfering effects of multiple steel layers (shadowing)	C	C	A
	Resolution versus detection of failures	C	A	C
Level of interpretation	Immediate readings	A	C	C
	Time expended for data interpretation for a given surface	B	B	C
	Calibration aspects[5]	C	C	C
Standards and guidelines	Standards	A	C	C
	Guidelines	A	A	A
Combination considerations	For a better implementation of the technique	Radar, IE, Magnetic	Radar, IE	Nothing
	For a better assessment	Magnetic	Radio	Magnetic, Radio
Safety parameters	Protection required for users and passers-by	C	B	A
Required staff and training time	Total crew size	C	A	A
	Required training time	B	B	B
Cost considerations[6]	Cost of implementation	C	B	B

[2]: some experts underline the difficulty to asses pre-tensioned prestressed structures with AE
[3]: the shadowing effect of the duct can reduce the signal but it is possible to keep 60 to 80% which can be sufficient in many cases [Scheel, 2003] Nevertheless the junction of the metallic ducts can disturb the measurement.
[4]: continuous monitoring can disable the diagnosis since the assessment is not immediate
[5]: calibration is destructive and consists in doing a window through the structure up to the cable
[6]: for information

(cable integrity and also, in the same time, quality of the grout), but its implementation is expensive and hazardous. A limitation or a rationalization of radiography investigations by a first sounding with other methods (magnetic, acoustic emission, impact echo) could be proposed. The magnetic methods are able to identify and to localize the ruptures on a cable.

Nevertheless, for a global assessment of the structure, neither the magnetic methods, nor the radiography can be helpful. A monitoring technique such as acoustic emission is able to localize areas where failures occur, at the global scale of the structure. But this localization is not accurate. Once this localization is done, magnetic technique could be very useful to localize the rupture with higher accuracy. In chosen areas, radiography could be performed to go further in the diagnosis and to define the condition of the whole tendon (presence of grout, defect in the duct…). Nevertheless, to go further and to establish a prognosis of the structure evolution, another important point is the definition of the origin of the rupture of the cable. Particularly, if there is a bad grouting what is the nature of the medium surrounding the cable or is there a favorable condition for the development of corrosion? If corrosion is involved what is its activity level? But for such level of investigation a windowing remains necessary.

The following describes an example where the techniques were combined. It concerns a prestressed concrete bridge located in Foix in the South of France. This bridge was placed under survey since 1995, because some recalculations have shown that a single rupture of cable could involve a sudden failure of the bridge. So a monitoring of the bridge by AE has been performed during a period of three years [Robert et al, 2000] in order to survey the behaviour of the bridge and to identify the ruptures.

The dimensions of the post-tensioned test beam are 2.10 m high and approximately 9.50 m long. The height of the web is 1.10 m and its thickness is 0.20 m. Its reinforcement is composed of vertical bars and 11 post-tensioned tendons, including five anchorages at the end stringer and six in the top.

During this period the five prestressed beams of the bridge were monitored and 13 events which have been linked to failures of wires or cables have been identified. One of the beams has cumulated 7 events which were all localized at its extremity. The intensity of the last event monitored was so high that the bridge owner decided to close the bridge and shortly after the bridge has been demolished.

During the bridge demolition, it was decided to perform an autopsy on the beam that presented the highest level of presumed defects in order to validate the acoustic monitoring. In addition, prior to the destruction of the beam (see Fig. 7.21), an experimental program to evaluate numerous non-destructive testing (NDT) methods was initiated. So, Impact Echo, radar and radiography were implemented on the areas were failures had been detected [Dérobert et al, 2002]. Radar was only used for the localization of tendons. For the radiographic investigation, a radiographic numerical system, called the digital phosphor system (DPS) which scans into a numerical film, has been used. Its major advantages, in comparison with the classical radiographic technique, consist of an accurate positioning of the prestressed ducts and tendons as well as of reinforcement bars. In the vicinity of the detected failures by

Fig. 7.21 Post-tensionned beam
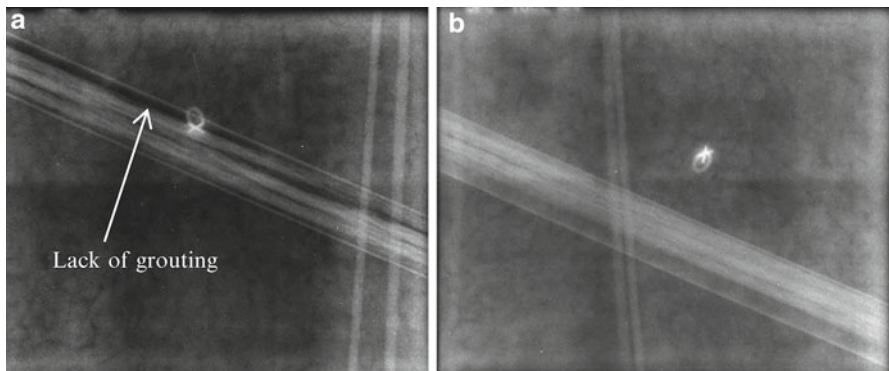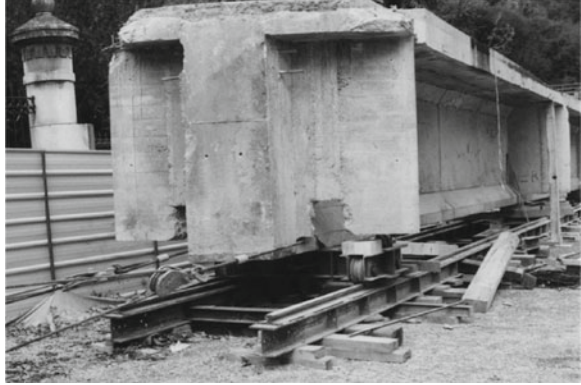

Lack of grouting

Fig. 7.22 Radiographic films

AE, two zones were investigated. The radiographic films obtained are presented on Fig. 7.22. The first zone revealed a complete lack of grouting (dark area above the cable) around the tendons (dark areas) in the central duct (Fig. 7.22a), while the second one indicates a correct injection in the central duct (Fig. 7.22b).

Even if the quality of the radiographic films was rather good, the technique was not able to reveal the presence of failures on the cable in these zones.

Another interesting approach of this study is the implementation of the IE technique for the detection of voids in the ducts. The results clearly emphasize the ability of the technique to detect the empty duct which was revealed by the radiography.

So, after performing NDT, the beam was completely destroyed by hydro-demolition. After completely removing the tendons, the autopsy permitted to confirm the fractures detected by AE. The observation of the cables showed that they were manually greased in order to provide adequate protection against corrosion given the age of the bridge. But in some specific locations, the lack of grease reflects stress corrosion with wire fracture and, in two cases, a cable fracture.

4 Benchmarking sites: examples

Even if the problem is more and more important, too few non destructive techniques are available for detecting the failures of prestressing cables. Moreover there is a lack of guidelines or recommendations regarding the implementation of these techniques for the diagnosis of ruptures of prestressing cables. Existing methods use very different approaches and are not efficient at the same scale.

Acoustic emission which is a monitoring technique can detect occurring ruptures and localize them. But it does not allow quantifying the number of broken wires which is nevertheless one of the more important information regarding a recalculation process of the structure. Magnetic techniques are able to localize existing ruptures but without possibility of quantifying the number of ruptures. Radiography is interesting by providing an image of the whole tendon but, up to now, it remains difficult to reveal the presence of wire failures due to insufficient resolution. Moreover radiography is hazardous and its implementation requires a protection area around the structure. Nevertheless, despite of this disadvantage which makes it rather heavy to implement, radiography can also provide information on the grouting quality which can be one of the origins of the failure of the cables, in case of corrosion for instance.

Our aim is to show that a combination of these three techniques should efficiently improve the assessment of prestressing cables. The main interest of the combination could be the gradual assessment of the cable integrity: firstly at the level of the whole structure by an acoustic monitoring, secondly on a part of the structure by magnetic techniques implemented on the supposed damaged cable if it is accessible, and finally at the scale of the cable, by radiography done on the damaged area.

Some benchmarking sites could be designed for this purpose. The rupture of the wires could be induced by means of an accelerated corrosion of the cables like it was proposed by Flicker and Vogel (see 2.3.3.) or by Sawade [Sawade, 2007]. In this last example, in a prestressed beam, a cable was treated with a solution of NH_4SCN and HCL and polarized with –1200 mV (Fig. 7.23). The cable has been monitored by magnetic flux leakage measurements at different time intervals.

Another study performed by Perrin et al [Perrin et al, 2009] also permitted to detect failures on a strand by acoustic emission on a simulated prestressed concrete structure (Fig. 7.24). A full anchorage was used and the strand was placed inside an injected duct. The full anchorages were composed by a concrete block with reinforcing bars and an anchorage head. A duct was placed on a half part of the strand. The anchorage B and the duct were injected with a cement grout. A corrosion cell was placed in the middle of the strand and a corrosive solution composed with 250 g/l of ammonium thiocyanate (NH_4SCN) was placed in the cell and kept at a constant temperature of 50°C due to liquid circulating from a boiler. This structure was instrumented with an acoustic emission monitoring system with 12 different sensors.

Such examples of simulated or simplified structures could be used for a reliable control of the cable ruptures by means of a corrosion accelerated process and for implementing the three techniques in combination. This should allow a better

Fig. 7.23 Laboratory prestressed beam for detecting a wire failure by magnetic flux leakage method [Sawade, 2007]
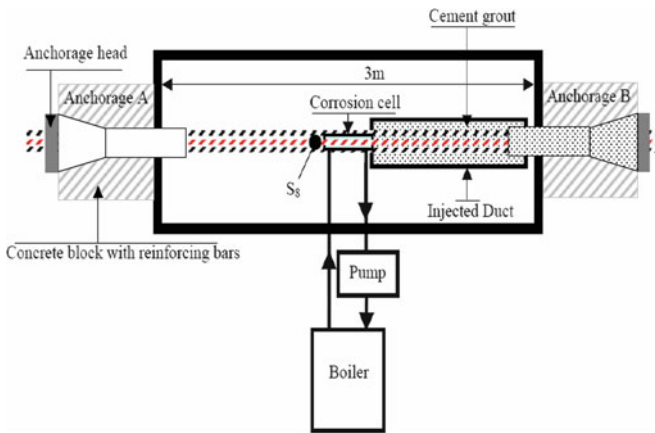

Fig. 7.24 Simulated structure for monitoring wire failure by acoustic emission [Perrin et al, 2009]

knowledge of the sensitivity of the different techniques and also their limits. So, some guidelines or recommendations regarding both implementation of the techniques and use in combination could be written.

5   Conclusions

The detection of broken wires or broken cables in prestressed concrete structures remains one of the most important challenges for Non Destructive Testing in Civil Engineering. This is a difficult topic due to the complexity of prestressing technol-

ogy. Indeed, in post-tensioned structures, the cables are placed in a duct (generally metallic) filled by a cement grout. The thickness of concrete above the duct can attain many decimeter, which makes difficult the assessment from the surface. Moreover a passive reinforcement mesh placed between the surface and the tendons can disturb the signal propagation of the NDT methods.

This chapter discussed three techniques which can be considered as relevant for this concern, since they have been successfully used on real structures:

– radiography, imaging technique allowing the assessment of both the grout and the duct. Identification of broken wires can be possible in some cases;
– magnetic techniques, able to detect broken wires up to 30 cm depth;
– acoustic emission, a monitoring technique able to detect and to localize ruptures when they occur.

These techniques were detailed, illustrated by case studies and their performances were compared. Standards or guidelines are available for radiography but not for magnetic techniques or acoustic emission. For this last technique, which is commonly implemented on bridges by several companies, some guidelines should be written.

Some possibilities of combination of these techniques and an example on a bridge beam were presented, but this example is probably unique. However, given the usual difficulties for investigating the cable integrity which requires a windowing to achieve a reliable diagnosis, the combination of the three techniques detailed above could be considered. Testing sites to define the sensitivity of the techniques and the added value of the combination should be also developed.

Finally there is also an important need of development of new methods, not only for the detection of broken wires but also for identifying the origins of the ruptures of cables (corrosion assessment, contamination of the cable environment by chlorides …). In a predictive approach, so as to predict new ruptures, reliable methods for measuring the speed of corrosion should be also developed.

References

AFGC-B7 (2005) Méthodologie d'évaluation non destructive de l'état d'altération des ouvrages en béton armé, Ed. D. Breysse et O. Abraham, Chap. B7 « Méthodes END gamma-radio », Presses de l'Ecole Nationale des Ponts et Chaussées.

Altschuler E., Pignotti A. (1995) Nonlinear model of flaw detection in steel pipes by magnetic flux leakage", NDT&E International, Vol.28, N°1, pp 35–40.

Andrade C., Alonso C. Sarría. J. (2002) Corrosion rate evolution in concrete structures exposed to the atmosphere, Cement and concrete composites, Vol.24, pp 55–64.

Andrade C., Martínez I., Castellote M., Zuloaga P. (2006) Some principles of service life calculation of reinforcements and in situ corrosion monitoring by sensors in the radioactive waste containers of El Cabril disposal (Spain), J. Nuclear Materials, Vol. 358, pp 82–95.

Andrade C., Sarria J., Alonso C. (1999) Relative humidity in the interior of concrete exposed to natural and artificial weathering, Cem. Concr. Res., Vol. 29, pp. 1249–1259.

Andrade C., Gonzalez, J.A. (1978) Quantitative measurements of corrosion rate of reinforcing steels embedded in concrete using polarization resistance measurements, Werkst. Korros., Vol. 29, N° 515.

ASTM C876-91, Standard Test Method for Half Cell Potentials of Uncoated Reinforcing Steel in Concrete.

Chauvin G. (2005) La réparation de la route de la Corniche à Marseille : les désordres, les investigations, le projet de réparation, les contraintes du maître d'ouvrage, les réparations, les difficultés rencontrées, le coût de l'opération », Xème colloque sur les Ouvrages d'Art, Toulouse, 19 et 20 octobre 2005, http://www.le-pont.com/Histo/programme/interventions/chauvin-corniche-marseille.pdf

Ciolko A.T., Tabatabai H. (1999) Nondestructive Methods for Condition Evaluation of Prestressing Steel Stands in Concrete Bridges", Final Report, Phase I: Technology Review, March 1999.

De Wit M. (2004) Acoustic monitoring for wire break detection – Case study, First Workshop of COST 534 "NDT assessment and new systems in prestressed concrete structures", ETH Zurich, Ed. Bernhard Elsener and Rob Polder, 13 October 2004

Dérobert X., Aubagnac C., Abraham O. (2002) Comparison of NDT techniques on a post-tensioned beam before its autopsy", NDT&E International, Vol.35, p.541–548.

Dufay J.C., Piccardi J. (1985) SCORPION, premier système de radioscopie télévisée haute énergie pour le contrôle non destructif des ouvrages d'art en béton précontraint », Bulletin de liaison des Laboratoires des Ponts et Chaussées, N°139, pp 77–84, Sep-Oct 1985.

Elsener B., Bóhni H. (1990) Corrosion Rates of Steel in Concrete, N.S. Berke, V.Chaker and D. Whiting (Eds.), ASTM STP 1065, pp. 143–156.

Feliú S., Gonzalez J.A., Andrade C. (1996) Multiple-electrode method for estimating the polarization resistance in large structures, J. Appl. Electrochemistry, 26, pp 305–309.

Fricker S., Vogel T. (2007) Site installation and testing of a continuous acoustic monitoring, Constr. Build. Mat., Volume 21, Issue 3, March 2007, 501–510.

Graves H.L., Tabatabai H. (1998) Acoustic Monitoring of Containment Tendons" Nuclear Engineering and design, Vol.181, pp.225–233.

Hillemeier B., Scheel H. (2004) Location of prestressing wire breaks with the remanent magnetism method – recent developments: application to highly reinforced concrete members and fast location of prestressing wire breaks in bridge decks and parking lots, Second FIB Workshop on Durability of post-tensioning tendons, , ETH Zurich, Ed. Bernhard Elsener, 11-12 October 2004.

Host H., Wichmann H.J., Hariri K., Budelmann H. (2008) Detection and Localization of Fractures and Flaws in Prestressed Tendons by means of Electromagnetic Resonance RF-Measurements, COST 534 "NDT assessment and new systems in prestressed concrete structures", Final Report, 2008.

Hovhanessian G., Laurent E. (2005) Ecoute acoustique et durabilité des ouvrages en béton précontraint », Journées GC'2005, Paris, 5 et 6 octobre 2005.

Hovhanessian G. (2005) Bilan de 10 années d'écoute acoustique, Colloque le Pont, Toulouse France, 19 et 20 octobre 2005.

Krause H.J., Wolf W., Glaas W., Zimmermann E., Faley M.I., Sawade G., Neudert G., Gampe U., Krieger J. (2000) SQUID system for magnetic inspection of prestressed tendons on concrete bridges, Proc. 15th WCNDT, Roma.

Laguerre L. (2003) Non destructive evaluation of slender steel members using elastic guided waves, Int. Symp. NDT-CE 2003, Berlin, Germany.

Makars J., Desnoyers R. (2001) Magnetic field techniques for the inspection of steel under concrete cover, NDT&E International, Vol.34, pp.445–456.

Mindess S. (2004) Acoustic Emission Methods, in CRC Handbook on Non-destructive Testing of Concrete, 2nd Edition, CRC Press, Boca Raton, Fl.

NF A 09-202 (1999) Principes généraux de l'examen radiographique, à l'aide de rayons X et gamma, des matériaux béton, béton armé et béton précontraint.

Perrin M., Gaillet L., Tessier T., Idrissi H. (2009) Acoustic emission for prestressing strands corrosion assessment", NDTCE'09, Nantes, France, June 30th-July 3rd, 2009.

Poston R.W., West J.S. (2004) North American Strategies for Monitoring, Maintenance and Repair of post-tensionning Tendons, Second FIB Workshop on Durability of post-tensionning ten-

dons, Swiss Federal Institute of Technology, ETH Zurich, Ed. Bernhard Elsener, 11-12 October 2004.

RILEM TC-154 EMC (2000) Electrochemical techniques for measuring corrosion in concrete", Recommendations, Mat. Str., Vol.33, 36 and 37, 2000 to 2004.

Robert J.L., Brevet P, Bruhat D., Gervais J.P. (2000) La surveillance acoustique-auscultation des OA: application au pont de Foix, Bull.AFGC, 2, pp 113–8.

Sawade G. (2007) Magnetic flux leakage measurement method, Final Workshop of COST 534, "NDT assessment and new systems in prestressed concrete structures", Univ. Paul Sabatier, Toulouse, France, 26-27 November 2007.

Sawade G. (2004) Magnetic leakage measurements on prestressed concrete, First Workshop of COST 534, "NDT assessment and new systems in prestressed concrete structures", ETH Zurich, Ed. B. Elsener and R. Polder, 13 October 2004.

Scheel H., Hillemeier B. (1997) Capacity of the remanent magnetism method to detect fractures of steel in tendons embedded in prestressed concrete, NDT&E Int., Vol.30, N°4, pp.211–216.

Scheel H., Hillemeier B. (2003) Location of Prestressing Steel Fractures, Concrete J. of Materials in Civil Engineering, Volume 15, Issue 3, pp. 228–234, May/June 2003.

Travers F.A. (1997) Acoustic Monitoring of Prestressed Concrete Pipe, Constr. Build. Mat., Vol.11, 3, pp. 175–187.

Wichmann H.J., Holst A., Hariri K., Budelmann H. (2003) Detection and localization of fractures in tendons by means of electromagnetic resonance measurement, Int.Symp. NDT-CE 2003, Berlin, Germany

Wood J.G.M., L'ingénierie forensique. Approche anglaise, Colloque Le Pont, Toulouse, 21-22 oct. 2008.

Woodward R.J., Williams F.W., Collapse of Ynys-y-Gwas bridge, West Glamorgan, Proc. ICE, Part 1, Vol. 86, pp. 1177–1191, 1989.

Yuyama S., Yokoyama K., Niitani K., Ohtsu M., Uomoto T. (2007) Detection and evaluation of failures in high-strength tendon of prestressed concrete bridges by acoustic emission, Constr. Build. Mat., Vol. 21, pp.491–500.