Corrosion protection of external tendons in post-tensioned concrete bridges

Prepared for Civil Engineering Division, Highways Agency

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Executive Summary

There has been renewed interest in the UK over the last ten years in the design and construction of post-tensioned concrete bridges with external unbonded tendons. This resulted from the moratorium that was placed on the construction of post-tensioned bridges with internal bonded tendons in 1992. The moratorium was placed following problems associated with grouting of the post-tensioning ducts and the difficulty of determining the condition of the tendons. It was envisaged that external post-tensioning would facilitate the inspection and replacement of the prestressing system.

During the period 1994 to 2000, TRL undertook a major project for the Highways Agency to investigate all aspects of the design and construction of post-tensioned concrete bridges with external unbonded tendons. This included an investigation of the environment inside the concrete box section in which the tendons are housed. The objective was to determine the corrosivity of the environment and thus the degree of corrosion protection required by the tendons.

To provide data on the environment inside concrete box sections a number of lengths of stressed post-tensioning strand, unstressed wires from post-tensioning strand and steel coupons were exposed in two externally post-tensioned concrete bridges. Samples were also exposed outside the structures. The temperature and humidity both inside the box sections, adjacent to the stressed samples, and outside the structures were also monitored.

To investigate variations in condensation along the length of a bridge and the risk that corrosion could vary within different parts of a structure, a second set of coupons was positioned nearer the end of one of the structures where condensation was more likely to occur. In addition a number of time-of-wetness probes were installed along the length of the structure to give an indication of when condensation occurred.

This report describes the results obtained over a five-year period and considers the implications for the degree of corrosion protection required, and the frequency and detail of the inspection of tendons in these structures.
1 Introduction

There has been increasing interest in the UK in recent years in the design and construction of post-tensioned concrete bridges with external unbonded tendons. This was given a significant boost in 1992 with the moratorium on the construction of post-tensioned bridges with internal bonded tendons as a result of problems associated with grouting of the post-tensioning ducts. It was envisaged that external post-tensioning would facilitate the inspection and replacement of the prestressing system.

To assist in the design of these structures the Highways Agency issued a Standard, BD 58 (Design Manual for Roads and Bridges 1994a) and an accompanying Advice Note, BA 58 (Design Manual for Roads and Bridges 1994b). These documents were based on a review of existing knowledge that included recommendations on where further research was required.

During the period 1994 to 2000, TRL undertook a major project for the Highways Agency to investigate all aspects of the design and construction of post-tensioned concrete bridges with external unbonded tendons. This included an investigation of the environment inside the concrete box section in which tendons are housed. The objective was to determine the corrosivity of the environment and thus the degree of corrosion protection required by the tendons.

To provide information on the environment inside a concrete box, stressed samples of post-tensioning strand, unstressed wires from post-tensioning strand and steel coupons were placed in the box sections of two bridges. In addition temperatures and relative humidities both inside and outside the box sections were monitored.

Monitoring started at the end of 1995 and continued for five years. The results obtained during the first few years showed that there could be considerable variation in condensation along the length of a bridge and that the risk of corrosion could vary within different parts of a structure. To investigate this further another set of steel coupons was exposed in one of the structures during 1998, at a location where condensation was more likely to occur. In addition a number of time-of-wetness probes were installed along the length of the structure to give an indication of when condensation occurred. The results obtained during the five years of monitoring, the conclusions drawn and their implications for structures of this type, are presented in the following sections.

2 Structures monitored

A description of the two structures monitored is given below.

2.1 Botley Flyover

The bridge is situated at the interchange of the A34 with the A420 on the west side of Oxford. There are two structures and they share a similar form of construction. Both are three span continuous overbridges with spans of 12.7m, 29m and 10.75m. The test samples and monitoring equipment were placed in the south bridge (Figure 1).

The bridges, which were built in 1972 and designed by E W H Gifford & Partners, are a combination of in situ and precast elements subsequently stressed together. The central section of the main span (approximately 60 %) comprises four precast box beams with an in situ deck slab. The
remaining end sections of this span and the two side spans consist of multicell box construction. Cross beams are positioned directly above each pier and diaphragms separate the precast beams from the multicell boxes.

A total of eight external unbonded tendons consisting of 19 no. 18mm diameter strands run the full length of the three spans between anchorages positioned at the deck ends. The tendons are located within the deck voids and are deflected by deviators within the cross beams, diaphragms and intermediate web stiffeners.

Strands within each tendon are individually sheathed except at the anchorages where the tendons are enclosed in plastic ducting. Tendon deflection at the deviators is achieved by saddles cut from lengths of rolled circular hollow section lined with PVC pipe. Corrosion protection is provided by a combination of grout and grease. At the anchorages the void between the duct and the cable is filled with grout. At the web stiffeners the voids are filled with grease. At the pier cross beams structural grade concrete was used. Drawings provided indicate that at the diaphragms grout was used to fill voids on the north bridge whereas grease was used on the south bridge.

Entry into each of the cells in both the in situ and precast sections of the bridge is through 600mm diameter access holes positioned in the soffit, on the side of the diaphragm or the side of beam. There is no physical access between cells and beams. The access points also act as vents and have lockable steel grilles. All access points except those for the end spans are positioned over the carriageway and lane closures are required in order to gain access.

Because of the access restrictions only two of the end span cells were inspected. There was no evidence of water leakage into either of the cells inspected. The surface of several intermediate web stiffeners had been painted with a bituminous coating. Only stiffeners on the outer edges of the structures seemed to have been treated in such a manner. The reason for this is not known. A grease treated wrapping tape has been extensively used at the ends of the anchorage ducting, presumably to seal the duct for grouting. The wrapping has also been used to seal sheathing where individual strands have been inspected.

### 2.2 River Camel Viaduct

The River Camel Viaduct is a single box that carries the A39 over the river Camel to the north of Wadebridge. It comprises nine spans, the outer spans being 37.5m and 42.5m, respectively and the inner ones 54m. It was designed by Gifford and Partners and opened to traffic in July 1993 (Figure 2).

The bridge is of in situ construction and was built span by span, the construction being from the approximate fifth point in one span to the fifth point in the following span. Each span was cast in ten pours with the anchor block being cast first.

The deck is post-tensioned with the VSL system, each tendon comprising 23-25 no. 15.7mm diameter strands in 140mm diameter HDPE ducts with a wall thickness of 8mm. The ducts are joined by heat shrink connections and were temporarily supported during construction to the approximate cable profile by suspension from the top slab. There are sixteen tendons over the piers and fourteen along the remainder of each span with ten in the end spans. The tendons were stressed ten days after the last pour.

![Figure 2 River Camel Viaduct](image)
The strands, which were designed to be replaceable, protrude approximately 1.5m at the live end anchorages to enable the tendons to be de-stressed. The protruding tendons are covered with an anchorage cap that is filled with Denso void filler. This is also used to protect the tendons where they pass through the anchorages and anchor block. The concentric tubes through the anchorage block enable the cable and anchorage assembly to be removed after the cables have been de-stressed.

3 Description of monitoring systems

Stressed strand samples, wires from free lengths of strand and weight loss coupons, were exposed within the box sections (Figure 3). Weight loss coupons were also placed outside the structures.

The stressed strand samples were loaded to 70% of their ultimate tensile strength and some were instrumented with load cells to record the load in the strand. Deflectors, with a radius of curvature of 2.5m, similar to the deviators found in typical bridges, were incorporated into some of the stressing rigs. HDPE pipe was placed between the strand and the deviator to simulate the actual interaction of strand and duct (Figure 4). This was to provide information on the performance of HDPE ducting under stress for typical environmental conditions.

The wires from lengths of strand and the weight loss coupons were used to give a measure of corrosion rates. Corrosion was monitored visually and the coupons were also used to provide quantitative data on corrosion rates. Unfortunately the weight loss coupons placed outside the River Camel Viaduct were stolen.

The temperature and humidity both inside and outside the two structures were recorded every hour. Within each structure, the air temperature, the surface temperature of the concrete and the humidity were recorded local to the samples. The samples in the River Camel Viaduct were positioned towards the centre of the bridge. However following the observation of condensation in one of the end spans it was decided to extend the monitoring to determine whether corrosion rates would be higher in areas where condensation had been observed. This was done by installing the following during August 1998:

- another set of coupons and unstressed wires was placed in the end span at the west end of the bridge;
- four time-of-wetness probes were positioned at the following locations: span 1 (west end of bridge) adjacent to the end diaphragm (TW1), span 2 near the original exposed specimens adjacent to north web (TW2N), span 2 near the original exposed specimens adjacent to south web (TW2S) and span 3 adjacent to intermediate diaphragm (TW3).

The time-of-wetness probes were constructed of two interlinked comb-shaped electrodes made of stainless steel. The interlinking teeth of the combs were maintained a fixed distance apart (<1mm) by bedding them in a layer of electrically insulating epoxy resin flush to their top surface. The overall probe dimensions were approximately 45mm×25mm×1.5mm. The presence of moisture on the probe was detected by measuring the electrical resistance between the two electrodes across the surface of the epoxy layer; when there was no moisture on the surface of the probe the resistance was high, but when moisture was present the resistance was low.

Figure 3 Weight loss coupons and unstressed wires at River Camel Viaduct
By using thermally conductive epoxy resin in both the construction of the probe and as the fixing method, the probe was maintained at the same temperature as the element on which it was fixed. Therefore if the environmental conditions were suitable for condensation to form on the element, it was mirrored on the probe and detected by the change in resistance.

The probes were mounted on top of the metal tube where it protruded from the diaphragms (TW1) and on end caps of anchorages (TW2N, TW2S and TW3), these being ‘mechanically’ and thermally connected to the tendons (Figure 5). During installation, a small ‘tank’ was temporarily formed on the top surface, filled with more thermally conductive epoxy resin and the probes placed in the top. When the epoxy had set, the result was a small block of epoxy, attached to the metal, with the probe at the top in a position as close to horizontal as possible.

The probes were connected to a constant voltage supply, with the logger measuring current. When the probes became wet, the resistance would fall and the current rise, hence small values represent dry conditions, and larger values wet.

4 Results

4.1 Strand samples and weight loss coupons
The loads in the strands on both structures remained stable after an initial settling-in period. The small fluctuations that occurred subsequently were probably caused by the components of the test rigs expanding and contracting due to the temperature variation (Figure 6). Monitoring of the strands in the River Camel Viaduct was discontinued in August 1998 to enable the time-of-wetness probes to be monitored.

The steel coupons and strands were visually inspected during each visit to the structures. Some of the weight loss coupons and wires from lengths of strand were periodically removed and returned to TRL where any rust that had formed was removed. This was done by immersion in Clarke’s solution (concentrated hydrochloric acid inhibited with stannous chloride and antimony trioxide to prevent attack on the underlying steel). The samples were then weighed to give the weight loss that had occurred during the exposure period. The corrosion was expressed as an equivalent loss in thickness and the results obtained after each exposure period are shown in Figure 7.

4.1.1 Botley Flyover
Spots of corrosion started to develop on both the samples of wire and the coupons exposed in the boxes fairly soon after installation, although it was much less pronounced than on the samples exposed outside. The horizontal coupons were more severely corroded than the vertical ones and corrosion was more pronounced on the top surface than underneath. After a year the top of the horizontal coupons had a light coating of rust speckled over the surface whereas the bottom surface and the two surfaces (front and back) of the vertical coupons only had a few spots of light surface rust on them. The amount of rust continued to increase and the corrosion on the two surfaces (front and back) of the vertical coupons remained similar over the five years of exposure. The condition of the samples after almost five years exposure is shown in Figure 8 and a comparison of the coupons at different ages is shown in Figures 9 and 10.
Figure 5 River Camel Viaduct: Time of wetness probe

Figure 6 River Camel Viaduct: Loads in strands
Figure 7 Weight loss measurements

Figure 8 Botley Flyover: Internal and external weight loss coupons after 58 months exposure
**Figure 9** Botley Flyover: Top surface of internal horizontal coupons after different periods of exposure

**Figure 10** Botley Flyover: Internal vertical coupons after different periods of exposure
These observations were confirmed by the results from the weight loss coupons that showed that corrosion in the box was low compared to that outside.

After five years the stressed strands were still generally clean with a few small specks of surface rust which covered about 10 to 15% of the surface. The rust was occasionally more developed in crevices between the wires. Condensation was sometimes observed on the strands in the test rigs during the visits to the structure.

4.1.2 River Camel Viaduct

Observations made at the River Camel Viaduct suggested that a similar pattern of corrosion had developed. Initially it appeared visually to be occurring at a slightly faster rate than at Botley although there was little to choose between the two sites after five years exposure. A comparison of the coupons at different ages is shown in Figures 11 and 12.

Small areas of localised rust staining were evident on the wires of the stressed strands and, as at Botley Flyover, it was occasionally more developed in the crevices between the wires. This may have been due to moisture from condensation collecting in the troughs between the wires. There was no evidence of pitting corrosion after five years exposure. The condition of a stressed strand after four years exposure is shown in Figure 13.

Samples of unstressed wire after four years exposure are shown in Figures 14, 15 and 16 at a magnification of approximately seven. Figures 14 and 15 show unstressed wires after the rust had been cleaned off. The former had been exposed outside Botley Flyover for 46 months and the latter had been exposed in the River Camel Viaduct for 48 months. The wire exposed inside the box appears in as-new condition whereas there is surface pitting on the wire exposed outside. Figure 16 shows the wire from Figure 15 before the rust had been removed.

During the visit to Wadebridge in December 1998, the end span at the east end of the structure was found to be damp with condensation on the soffit of the top slab, the walls of the box and the ducting. The visit was made during a period of heavy rain and there was a considerable leakage of water through the expansion joints into the anchorage chamber that created a very damp environment. The condensation reduced away from the end of the structure. The sections where the monitoring system and coupons had been installed, and the end span at the west end of the bridge were dry. No condensation was observed during the visits made in 1999 and 2000.

Figure 11 River Camel Viaduct: Top surface of internal horizontal coupons after different periods of exposure
**Figure 12** River Camel Viaduct: Internal vertical coupons after different periods of exposure

**Figure 13** River Camel Viaduct: Corrosion on stressed strand after 48 month exposure
Figure 14 Botley Flyover: Unstressed wire with rust removed after 46 months exposure outside

Figure 15 River Camel Viaduct: Unstressed internal wire with rust removed after 48 months exposure
The coupons installed in the end span in August 1998 showed a similar pattern of corrosion to the coupons installed in 1995. There was light corrosion with light surface rust on the top surface of the horizontal coupons and a few spots of rust on the vertical coupons and on the underside of the horizontal coupons. Vertical and horizontal coupons were removed after 12, 24 and 28 months for weight loss measurements and the average annual thickness losses were 0.3µm for the vertical coupons and in the range 1.0µm to 1.3µm for the horizontal coupons. The results for the vertical coupons were similar to those measured for the first set of samples (Figure 7) but the results for the horizontal coupons were over 50% higher. It is not possible to state whether this is a significant difference as the absolute values of corrosion rate are extremely low.

4.2 Temperature and humidity

Figures 17 to 19 show the internal and external temperatures and humidities recorded at the two structures. They show that the environment within the structures is more stable than that outside and that the internal temperature and humidity followed the general trend of the ambient atmospheric conditions although values were less extreme. Figure 17 shows that it was usually warmer inside the boxes than outside.

The external daily temperature cycles and fluctuations in relative humidity were generally more extreme at the River Camel Viaduct than at Botley Flyover possibly because it was in a more exposed environment.

Figure 19 shows the temperatures and humidities measured at the River Camel Viaduct during the second half of 1998, both external to the box section and adjacent to the two sets of coupons ie those installed originally and those installed near the end of the structure. The internal temperatures at the two locations are virtually identical but the humidities measured in the end span are generally, but not always, higher than those measured nearer the centre of the bridge.

4.3 Time-of-wetness measurements

The time-of-wetness probes were installed in September 1999 and the results from the first three months monitoring are shown in Figure 20.

Readings taken from the probes indicate the degree of wetness and are related to the electric current flowing through the probe. As described in Section 3, when the probes are dry the currents are low but when condensation occurs the current increases and higher readings are obtained. The results in Figure 20 show that higher currents were measured during periods when the relative humidity was high. The relative humidities greater than 100% are due to calibration errors.

Figure 21 shows time-of-wetness and relative humidity readings plotted over a shorter period. The individual time-of-wetness readings can be seen more clearly with the highest readings corresponding to the sensor nearest the end of the bridge (TW1).

However the actual time-of-wetness is likely to be a better indicator of condensation than the absolute values measured. Table 1 gives the number of hours the probes gave readings greater than 0.05. This is an arbitrary value taken after inspection of Figures 20 and 21 as being representative of the transition from low (dry) to high
Figure 17 Botley Flyover: Average daily temperatures

Figure 18 Botley flyover: Hourly temperatures and humidities

Figure 19 River Camel Viaduct: Hourly temperatures and relative humidities at original and new locations
Figure 20 River Camel Viaduct: Results from time-of-wetness and humidity probes over a three month period

Figure 21 River Camel Viaduct: Results from time-of-wetness and humidity probes over a seven day period
that the average annual rate is decreasing (Figure 7). Subsequent years of exposure, although there are indications the corrosion observed has continued to increase during the particles settling on the surface of the steel. The amount of top surface of the coupons was probably due to dust and strands. The increased severity of the corrosion on the years and there were also spots of corrosion on the wires completely covered with light surface corrosion after two horizontal coupons in the box sections was almost exposed to the wind and rain. However, these results need to be treated with caution as the characteristics of the probe changed over the monitoring period and this requires further investigation. The results obtained over the subsequent 12 months showed a similar pattern although the relationship between higher currents and high relative humidity was less clearly defined. In general higher readings also coincided with rising air temperatures. It was noted that spots of corrosion were present on the probes and this may have affected the readings. The number of hours during which higher readings were recorded is shown in Table 1. The results showed the same pattern as previously although a lower cut-off was used than during the first period. This reduction may have been due to the corrosion that was observed on the probes which may have increased their resistance and thus reduced the current.

5 Discussion

5.6 Corrosion rates

It has been found that corrosion rates on composite steel bridges are considerably reduced if the steel beams are enclosed (Mckenzie 1991). Table 2 shows the corrosion rates measured on a number of bridges, both inside and outside the enclosure. It can be seen that even though corrosion rates inside the enclosure are considerably less than those outside they are still higher than those measured inside the concrete boxes at Botley Flyover and the River Camel Viaduct. The results obtained indicate that even though there may be a reduction in condensation away from the end of the structure. The probe in the end span was wet for about 10% of the time whereas the probes in the second and third spans from the end were wet for about 1% of the time. However these results need to be treated with caution as the characteristics of the probe changed over the monitoring period and this requires further investigation.

The additional weight loss coupons installed nearer the west end of the River Camel Viaduct in August 1998, in an area where condensation was more likely to occur, provided information on whether corrosion rates varied along the length of the structure. The corrosion rate on the horizontal coupon after 12 months was higher than that recorded on the original samples and the rate of corrosion after 28 months was about 50% higher. It is possible that the increased condensation nearer the end of the structure caused the higher corrosion rate but the difference between the two sets of coupons in absolute terms is very small and it is not possible to draw firm conclusions.

While the results obtained to-date show that the corrosivity inside a concrete box is relatively low, the spots of rust observed on unprotected steel strands indicate that some form of corrosion protection is necessary and that bare wires are not an option. However, indications are that simple corrosion protection measures are all that is required. The only prerequisites are that the tendons are inspectable and the box is designed to prevent the ingress of contaminants.

Table 1 Hours during which time-of-wetness measurements were greater than cut-off

<table>
<thead>
<tr>
<th>Date</th>
<th>Cut-off</th>
<th>Number of hours monitored</th>
<th>Time-of-wetness probe (hours)</th>
<th>TW1</th>
<th>TW2</th>
<th>TW3</th>
<th>TW4</th>
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<tr>
<td>Sept – Dec 1999</td>
<td>0.05</td>
<td>1357</td>
<td>130</td>
<td>1</td>
<td>12</td>
<td>35</td>
<td></td>
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<tr>
<td>Dec 1999 – Jan 2000</td>
<td>0.05</td>
<td>1399</td>
<td>116</td>
<td>3</td>
<td>48</td>
<td>15</td>
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<tr>
<td>Feb – June 2000</td>
<td>0.004</td>
<td>3382</td>
<td>528</td>
<td>0</td>
<td>17</td>
<td>6</td>
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<tr>
<td>Aug – Dec 2000</td>
<td>0.002</td>
<td>2712</td>
<td>153</td>
<td>0</td>
<td>12</td>
<td>20</td>
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(damp) conditions. They show that the time-of-wetness was greatest in span one (TW1) but that the probe in span three (TW3) was subjected to condensation for longer than those in span two (TW2N, TW2S).

The results obtained over the subsequent 12 months showed a similar pattern although the relationship between higher currents and high relative humidity was less clearly defined. In general higher readings also coincided with rising air temperatures. It was noted that spots of corrosion were present on the probes and this may have affected the readings. The number of hours during which higher readings were recorded is shown in Table 1. The results showed the same pattern as previously although a lower cut-off was used than during the first period. This reduction may have been due to the corrosion that was observed on the probes which may have increased their resistance and thus reduced the current.

Table 2 Typical corrosion rates in various environments

<table>
<thead>
<tr>
<th>Bridge</th>
<th>Location of coupons</th>
<th>Period of exposure (months)</th>
<th>Annual corrosion rate (µm)</th>
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<tr>
<td>Externally post-tensioned concrete structures</td>
<td></td>
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<td></td>
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<tr>
<td>Botley</td>
<td>In concrete box</td>
<td>58</td>
<td>0.5</td>
</tr>
<tr>
<td></td>
<td>Exterior</td>
<td>58</td>
<td>5-6</td>
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<tr>
<td>River Camel</td>
<td>In concrete box</td>
<td>60</td>
<td>0.5</td>
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Structures with enclosed steel beams

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<th>Location of coupons</th>
<th>Period of exposure (months)</th>
<th>Annual corrosion rate (µm)</th>
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<tr>
<td>Conon</td>
<td>Enclosure</td>
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<td>18</td>
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<td>Tees</td>
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<td>Second Severn crossing approach roads</td>
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<tr>
<td></td>
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¹These bridges were monitored by TRL for a local authority.

During the first three years of monitoring, information on condensation was limited to observations made during the occasional visit to the structures. The time-of-wetness probes installed during September 1999 have provided a better indication of the amount of condensation that occurs at the River Camel Viaduct. The results indicate that there is a reduction in condensation away from the end of the structure. The probe in the end span was wet for about 10% of the time whereas the probes in the second and third spans from the end were wet for about 1% of the time.

## External Materials

- [Mckenzie 1991](#).
- [TRL](#) for a local authority.

<table>
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<th>Location of exposure rate</th>
<th>Period of corrosion</th>
<th>Annual corrosion rate (µm)</th>
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Structures with enclosed steel beams

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<th>Location of coupons</th>
<th>Period of exposure (months)</th>
<th>Annual corrosion rate (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conon</td>
<td>Enclosure</td>
<td>17</td>
<td>2 – 3</td>
</tr>
<tr>
<td></td>
<td>Exterior</td>
<td>17</td>
<td>18</td>
</tr>
<tr>
<td>Tees</td>
<td>Enclosure</td>
<td>17</td>
<td>2-3</td>
</tr>
<tr>
<td></td>
<td>Exterior</td>
<td>17</td>
<td>49</td>
</tr>
<tr>
<td>Second Severn crossing approach roads</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Enclosure</td>
<td>12</td>
<td>1 – 6</td>
<td></td>
</tr>
<tr>
<td>Exterior</td>
<td>12</td>
<td>35 – 90</td>
<td></td>
</tr>
<tr>
<td>County bridges¹</td>
<td>Enclosure</td>
<td>12</td>
<td>3 – 8</td>
</tr>
<tr>
<td></td>
<td>Enclosure</td>
<td>12</td>
<td>3 – 9</td>
</tr>
<tr>
<td></td>
<td>Enclosure</td>
<td>12</td>
<td>3 – 7</td>
</tr>
</tbody>
</table>

¹These bridges were monitored by TRL for a local authority.


5.7 Corrosion protection systems

The most common methods of corrosion protection in current use are to house the tendons in wax or grout filled ducts. This has the disadvantage that tendons cannot be inspected directly. For grouted systems it is necessary to locally remove the sheathing and expose the tendons. For wax filled ducts strands have to be withdrawn and examined external to the duct. However the low corrosivity found in the concrete box sections that were monitored shows that as long as there is no evidence of leakage of deleterious materials into the box then the frequency and detail of tendon inspection can be kept to a minimum.

Coating systems that provide corrosion protection without requiring the tendons to be housed in a duct offer the ideal solution. The strands can be examined along most of their length for corrosion and wire fractures, while the coating provides protection against the limited corrosion that takes place in the box. At locations where strands are not visible i.e. where they pass through deviators and at anchorages, the unwinding of fractured wires would provide evidence of corrosion.

Coating systems available include:

- galvanising;
- paint;
- epoxy coating.

All these systems have their limitations. Galvanising has the advantage that it is not easily damaged in handling and installation, and BA 58 states that ‘Unducted galvanised tendons have the advantage of being easily inspectable throughout their length’. However it has not been used in bridges in the UK and it is believed that there are several reasons for this:

- it is a sacrificial coating and is consumable with time in a corrosive environment;
- concern among engineers about the risk of hydrogen embrittlement;
- cost; an unpublished whole life cost study has shown that of four options considered for protecting external tendons (galvanising, tendons in wax filled ducts, tendons in grout filled ducts with wax at the anchorages, and individually sheathed strands in wax filled ducts), galvanising was the most expensive.

Paint systems would be at risk of damage during installation and be difficult to apply after installation, as it would only be possible to coat the exposed surfaces of the outer wires. Any subsequent relative movement of individual wires would lead to a risk of ingress of moisture between wires and corrosion of unprotected steel. Epoxy coated strands have been used in the USA but there is concern about pinholes and local damage to the coating during installation and problems such as poor adhesion that cast doubt on its use.

An alternative solution would be to use individually sheathed strands in grease filled sleeves. This system has the advantage that the strands are protected against corrosion yet fractures of individual wires can be detected by looking for deformations in the sheath caused by movement of the wires when they fail. This has been done previously on structures where wire failures have occurred, by shining a torch focused to a pencil beam along the surface of each strand to cast shadows behind any irregularity in the sheathing (Brooman and Robson 1996). The limitation of the method is that it is not possible to detect fractures within the anchor block and at deviators.

The first eight externally post-tensioned bridges built in the UK all used individually sheathed strands and wire fractures were found in two of them. In one instance the strands were protected by Bridon’s Metal A - an aluminium resin - and individually sheathed within a 38mm diameter PVC sleeve. Failures were attributed to the presence of aluminium in the resin although the exact cause was never unambiguously determined (Porter 1985). In the second instance failures were attributed to problems during construction. On both bridges the strands were in PVC sleeves and this was also considered to be a contributory factor although this was not conclusively proven. No problems have occurred in the remaining six bridges. Strands were housed in PVC sleeves in one, and polypropylene sleeves in the remainder.

Another advantage of individually sleeved strands is that the corrosion protection is applied under factory controlled conditions, before delivery to site. Thus site operations are limited to ensuring that the tendons are properly stored before construction and not damaged during installation. However care is required where strands are protected at anchorages and where they pass through deviators. The use of plastic lined deviators should reduce the risk of damage during installation.

Strands in grease filled polypropylene sleeves are currently commercially available. One system uses a multi-layer protection whereby the sleeved strands are themselves housed in wax or grout filled HDPE ducts. The use of grout or wax filled ducts increases the cost, and makes the strands difficult to inspect. Given the low corrosivity of the environment it is questionable whether this additional protection is really necessary.

Of the currently available corrosion protection systems, individually sheathed strands appear to offer the best compromise between providing some corrosion protection whilst allowing the strands to remain inspectable.

5.8 De-humidification

Another possible corrosion protection option that could be considered is de-humidification. There is little doubt that it could further reduce corrosion subject to dealing with some of the problems outlined below (e.g. leakage). This would allow the tendons to remain unprotected and thus enable them to be visually inspected although there would still be problems of inspecting them adjacent to the anchorage and where they passed through deviators and diaphragms.

However it is likely that the cost of installing and maintaining a system would far outweigh any savings in corrosion protection. Another concern is that the greatest risk of corrosion is due to leakage of water and de-icing salts into the box. This would present a local problem and
a de-humidification system may not be able to prevent corrosion occurring on tendons subjected to leakage. Other concerns are listed below:

- would it cope with sudden changes in temperature?
- does the environment need to be sealed from the atmosphere? If not how much leakage can be allowed?
- does it completely prevent condensation?
- does it prevent corrosion completely or reduce the rate - if the latter then by how much?
- would it dry out the concrete and increase the risk of carbonation?

It would appear that the capital and running costs, coupled with the doubts about its effectiveness, particularly where leakage is present, mean that it is unlikely to provide a cost effective solution.

It is understood that it is planned to install a de-humidification system in the steel box sections of the Oresund bridges in Denmark (Gedge 1999). It has also been used on other bridges in Denmark. Further information is required; in particular on the costs of installing and maintaining the system and whether they outweigh any savings in corrosion protection.

### 6 Conclusions

The results obtained during the five years of monitoring have shown that:

- conditions inside the two bridges are more stable and less extreme than the outside environment;
- the corrosion on samples inside the structures is much less than outside;
- the corrosivity of the environment inside concrete box girder bridges is very low, less than that inside a bridge enclosure.

Initial findings from the coupons installed near the ends of the structure in the River Camel Viaduct show higher corrosion rates on the horizontal coupons and the time-of-wetness probes indicate that condensation is more frequent nearer the end of the structure. However there is insufficient data to draw firm conclusions but the results indicate that corrosion rates can vary along the length of a structure and that they are higher at locations where condensation occurs.

It is considered that, despite the low corrosion rates, bare tendons are not an option and that some form of corrosion protection is required. However the research demonstrates that the risk of tendon corrosion is low if the interior of the box remains sealed from de-icing salts. Inspection of these structures should therefore focus on looking for evidence of the ingress of de-icing salts and maintenance should focus on ensuring that this does not occur.

The most common methods of corrosion protection in current use are to house the tendons in wax or grout filled HDPE ducts. The findings indicate that there is little risk of corrosion of the tendons as long as the concrete box sections remain dry and free of contamination. Therefore, where this is the case, direct inspection of the tendons can be limited to a small number of spot checks.

Of the corrosion protection systems available, individually sleeved strands have the advantage that the corrosion protection is applied under factory controlled conditions, before delivery to site, and the performance of individual strands in polypropylene sleeves has a good track record in the UK. In addition, it is possible to inspect the strands along most of their length and to detect individual wire failures.

The installation of de-humidification systems to further reduce the risk of corrosion is likely to be difficult to justify on economic grounds. There is also doubt as to whether it would be effective in areas where it is most needed i.e where leakage occurs.

### 7 Acknowledgements

The work described in this report was carried out in the Infrastructure Division of the TRL Limited. The authors would like to acknowledge all the staff who were involved in the project, in particular Mr M Mckenzie and Mr A Frost. The authors are also grateful to Cornwall County Council and Oxfordshire County Council for permission to install the monitoring systems in the structures.

### 8 References

Abstract

A number of lengths of stressed post-tensioning strand, unstressed wires from post-tensioning strand and steel coupons, were exposed in the box sections of two externally post-tensioned concrete bridges. Samples were also exposed outside the structures. The temperature and humidity both inside the box sections, adjacent to the stressed samples, and outside the structures were also monitored. Time-of-wetness probes were positioned along the length of one of the structures. The objective was to determine the corrosivity inside the box sections and thus the degree of corrosion protection required by externally post-tensioned tendons. Results over five years indicate that although the corrosivity within a concrete box section is much lower than outside, bare tendons are not an option and some form of corrosion protection is required.

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