

Main Cable Corrosion Protection by Dehumidification – Experience, Optimization and New Development

Matthew L. Bloomstine

Chief Project Manager, COWI A/S, Denmark, mlb@cowi.dk

ABSTRACT: Corrosion of main cables on suspension bridges is a wide spread, well known and very serious problem. The safety of a great number of suspension bridges is compromised due to hidden corrosion that reduces the load carrying capacity of the main cables. Corrosion protection of main cables by dehumidification has over the last 13 years been proven to be in all ways superior to earlier so called traditional corrosion protection systems. Dehumidification is the only method that actually prevents corrosion, whereas other methods can at best only slow down corrosion.

This paper describes the development of corrosion protection of steel bridge components by dehumidification over the last 40 years and in particular the application of this technique to the main cables of suspension bridges. Experience from existing systems, the world-wide status for main cable systems, optimization methods and new developments are also described.

1 INTRODUCTION

Numerous examples of serious suspension bridge main cable corrosion have been discovered in USA, Europe and Japan. Many of the suspension bridges in USA are quite old; several are over 100 years, so it is not especially surprising that there is serious corrosion in the main cables of many of these bridges. More surprising are reports from Europe and Japan, where relatively young bridges; 5 – 30 years, have serious corrosion problems. Even more surprising is the fact that the main cables on many of these bridges have been well maintained and regular external inspections have revealed no signs of corrosion. This clearly shows that all suspension bridge owners/operators, no matter the age of the their bridge, should instigate measures to determine the condition of the main cables and protect them from corrosion by the best means possible, which has been proven to be dehumidification. This is the only method that actually prevents corrosion and does so by providing a dry and noncorrosive atmosphere inside the cables.



Figure 1 Corrosion on main cables aged roughly 30 and 8 years

Due to the above mentioned serious corrosion problems the use of existing dehumidification technology was further developed in Japan and Denmark during the 1990s for application on suspension bridge main cables. The goal was to completely prevent corrosion. There is currently 13 years of experience with dehumidification of suspension bridge main cables in Asia and Europe and the systems are showing excellent results.

2 GENERAL DESCRIPTION OF CORROSION PROTECTION BY DEHUMIDIFICATION

Dehumidification has been utilized as corrosion protection for more than 50 years. Dehumidification is based on the fact that steel does not corrode when the relative humidity (RH) of the local atmosphere is below 40%. This was proven by research at MIT Corrosion Laboratory lead by Professor H. H. Uhlig. Between 40% and 60% RH corrosion can occur, though at a very low rate. When the relative humidity exceeds 60% the rate of corrosion increases dramatically. The relationship between RH and the rate of corrosion is illustrated below in figure 2.

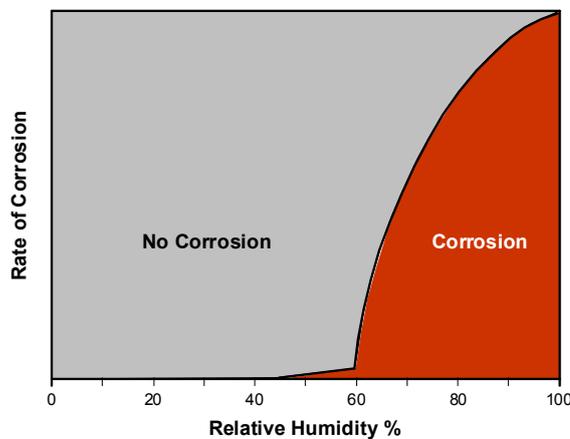


Figure 2 Relationship between RH and rate of corrosion (Prof. H. H. Uhlig, MIT Corrosion Laboratory)

A dehumidification system for a steel bridge structural element (see examples in section 3) is composed of relatively few elements. A dehumidification plant provides sufficiently dry air and circulates it inside the structural element, ensuring that the inner surfaces are protected from corrosion. The main components of the dehumidification plant are a electrical/control panel, a dehumidification unit and a fan unit as illustrated in fig. 3.

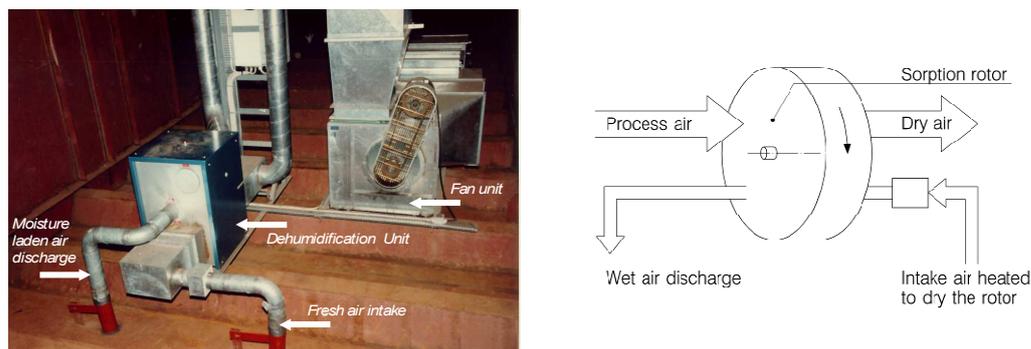


Figure 3 Typical dehumidification plant and diagram of active sorption dehumidification unit

The dehumidification unit is generally based on active sorption, as it is efficient for virtually all air conditions, i.e. there are practically no temperature and relative humidity limits. This method works by binding the moisture in the process air to a hygroscopic material (a sorbent). A dehumidification unit based on active sorption contains a rotor which is built up of many small pipes, coated with a sorbent, most commonly lithium chloride. The process air is forced through

the rotor and its moisture is absorbed under this process, resulting in dry air. The rotor turns very slowly, allowing time for the process. On the opposite side of the rotor, intake air is heated and blown through, which dries out the sorbent coating. This air becomes moisture laden and is subsequently discharged. A dehumidification unit with active sorption is shown in the picture in figure 3 and the principal is illustrated in the diagram.

3 EXPERIENCE WITH DEHUMIDIFICATION OF BRIDGE STRUCTURES

Corrosion protection of steel bridge structures by dehumidification was pioneered and developed by COWI in Denmark and there is currently over 40 years of experience from various steel bridge structures. This development started with the Little Belt Suspension Bridge that was constructed during 1965 to 1970. Dehumidification systems were designed and installed in the box girder and the anchor chambers (protection of cable strands) during construction. The dehumidification systems each include a dehumidification plant that produces dry air and a circulation system that ensures that dry air is circulated in all areas of the structures. The original systems perform effectively are still in service and have required a minimal amount of maintenance. The condition of the strands, splay saddle and other elements in the anchor chamber is as new. In the box girder shiny untreated steel plates were hung up at various isolated locations and these are also still as new, see figure 4.



Figure 4 Little Belt Suspension Bridge and untreated steel plate in bridge girder

The development continued on the next major bridges to be built in Denmark in the 1980s, the Faroe Bridges, where further applications were developed and applied. These two adjoining bridges have steel box girders with lengths of 1.6 and 1.7 km that are protected by dehumidification. The southernmost of the bridges includes a cable-stayed bridge and the lower cable anchorages are protected by the dry atmosphere in the bridge girder, whereas the upper cable anchorages are protected by a separate dehumidification system in the anchorage boxes at the top of the pylons. Systems were also installed in the abutment rooms on both bridges to protect the expansion joints and other structures located here.

These successes were followed up by systems on the Great Belt Bridge in Denmark, the Humber Bridge in England, the Högakusten Bridge in Sweden, the Oresund Bridge between Denmark and Sweden, the Pont de Normandie Bridge in France, the Stonecutters Bridge in Hong Kong and numerous other major bridges in many countries. It has virtually become a worldwide standard to apply dehumidification to bridge box girders and anchor chambers, as it is recognized as the most effective and economical means of corrosion protection. Dehumidification can be incorporated in the design of the bridge, or it can be applied as a retrofit, such as in the case of the box girder of the Humber Bridge in England.

All this experience from dehumidification of steel bridge structures over a period of about 30 years led to the development of dehumidification systems for main cables as the optimal system for corrosion protection. Since the first application on main cables in 1998 dehumidification of main cables has been continuously developed and is now internationally accepted as the optimal method for main cable corrosion protection.

4 CURRENT WORLD-WIDE STATUS FOR DEHUMIDIFICATION OF MAIN CABLES

4.1 *Systems in service*

There are currently 21 suspension bridges in a total of 8 different countries where dehumidification has been installed on the main cables as described below. As far as we know these systems are generally performing well, though some problems have been reported and suitable modifications have been carried out.

The development of dehumidification systems for main cables began in the 1990s with studies being carried out in both Japan and Denmark. The systems for main cables were based on tried and proven technology as a natural extension of earlier bridge projects.

The first bridge with dehumidification of the main cables was the Akashi-Kaikyo Bridge in Japan, the world's longest suspension bridge with a main span of 1,991 m opened in 1998. The dehumidification system was integrated in the bridge's design and installed during construction. Based on the experience from the Akashi-Kaikyo Bridge the operator Honshu-Shikoku Bridge Expressway Company Limited (HSBE) decided to install dehumidification on the main cables of all their suspension bridges. To date they have installed systems on 5 new suspension bridges and 7 existing suspension bridges in Japan.

In 2008, after 10 years of service, the main cables of the Akashi-Kaikyo Bridge were opened and wedged for inspection. The purpose of the inspection was to verify the effectiveness of the dehumidification system. According to HSBE Newsletter No. 38, July 2009, the cables were completely dry and the wires were in the same condition as at the time of construction.

The first suspension bridge outside of Japan to be retrofitted with dehumidification of main cables was the Little Belt Suspension Bridge in Denmark with a main span of 600 m, see figure 4. The bridge opened in 1970 and the dehumidification system was installed on the main cables in 2003. Research and testing of sealing systems and on-site testing of injection and flow parameters were carried over several years before the final project was developed and tendered. This system has been performing well for 8 years and no leakage has developed, as documented by the monitoring system. The drying out process was also documented by the monitoring system and took only a few days. The dehumidification plants have been inspected once a year and no maintenance has been necessary yet.

Also during 2003 a dehumidification system was installed on the main cables of the 40 year old Aquitaine Bridge in France during a retrofit project where the entire cable system was replaced. This system has also been performing well since installation.

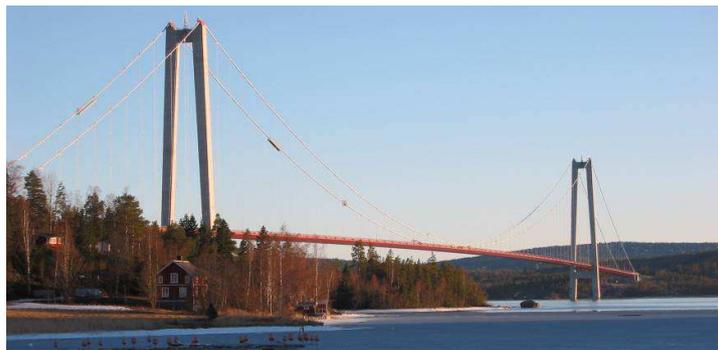


Figure 5 The Högakusten Bridge during installation of dehumidification system

The Högakusten Bridge in Sweden has a main span of 1,210 m and opened in 1998, see figure 5. There were already serious problems with water intrusion and corrosion of cable wires after 5 years. A dehumidification system was installed on the main cables during 2005 and a massive amount of water in the cables was dried out and the relative humidity brought down below the corrosion threshold. Data from the monitoring system has shown that the amount of water removed from the cables corresponds to about 3% of the void volume in the cables and this took about 1.5 years. The system has been performing well, though there has been a problem

with one of the transition shrouds outside one of the anchorage chambers, see section 6.2 for further information.

In Great Britain there are three major suspension bridges and dehumidification systems have been installed on the main cables of all three of these during 2007 to 2010. These are the Forth Road Bridge opened in 1964 with a main span of 1,006 m, the Severn River Crossing opened in 1966 with a main span of 988 m and the Humber Bridge opened in 1981 with a main span 1,410 m. The Humber Bridge was also earlier retrofitted with dehumidification systems for the box girder and the tower saddles in the 1990s.

Dehumidification of main cables has also been installed on suspension bridges in China and Korea. In China dehumidification of main cables was incorporated in the design of the Rung Yang Bridge. In Korea dehumidification of main cables was incorporated in the design of the Gwan Yang Bridge and installed on the existing Yong Jyong Bridge.

4.2 Current projects and standards

At the current time there are at least six projects for dehumidification of main cables under various states of progress as described below. Furthermore, authorities in two countries, Japan and Norway, currently require dehumidification of main cables as a standard. As mentioned in section 4.1, HSBE in Japan requires dehumidification of main cables on all their suspension bridges. In Norway the state authorities have required dehumidification of main cables in their bridge design standard (Bruprosjektering, Normaler, Håndbok 185) since 2009. Current projects in Norway include dehumidification, see below.

There are currently at least 6 different projects commencing in 4 different countries as described below. Together with the systems already in service there are at least a total of 27 systems in 11 different countries.

In Sweden a system is currently being installed on the Älvsborg Bridge in Gothenburg. The project is expected finished in August this year. This is an integrated system and further information is included in section 7.2.

In Norway two projects are currently progressing. The Hardanger Bridge with a main span of 1,310 m is currently under construction and is expected finished in 2012, see figure 6. This is an integrated system and further information is included in section 7.2. The Hålogaland Bridge with a main span of 1,145 m is currently preparing for tendering, see figure 6.



Figure 6 The Hardanger and Hålogaland Bridges, Norway

In Qatar 2 twin suspension bridges with unique circular towers, the Lusail Bridges, are to commence construction this year. The system for these bridges is a fully integrated system as described in section 7.2.



Figure 7 The Messina Bridge, Italy – world record span of 3,300 m

In Italy the Definitive Project (Progetto Definitivo) for the Messina Bridge with a world record span of 3,300 m has been completed, see figure 7. An integrated system has been designed encompassing the 4 main cables, each with a diameter of 1.1 m, the triple box girder and the steel towers. The anchorage chambers are designed with separate dehumidification systems.

5 DETAILS OF DEHUMIDIFICATION SYSTEMS FOR MAIN CABLES

A system for corrosion protection of main cables by dehumidification consists of the following three main components:

- A dry air system capable of producing and blowing dry air through the main cables.
- A sealing system for the main cables, including cable bands, saddles and other connected components.
- A control and monitoring system.

5.1 *Dry air system*

The dry air system produces dry air and blows it through sections of the main cables. The system assures overpressure inside the sealed cable system. While the sealing system may have minor imperfections in the form of small leaks, no water or moisture will enter the cables, as the overpressure will prevent this. The dry air system is made up of the following main components:

- Dehumidification plant(s).
- Injection and exhaust points.
- A layout, such as shown in figure 15, is developed for the dehumidification system. The layout defines the locations of the dehumidification plant(s), buffer chamber(s) (see description of buffer chamber in section 6.4), injection and exhaust points as well as the flow sections.

The main components of a dehumidification plant are a dehumidification unit, a fan, an electrical board, filters and ducting, such as illustrated in figure 8. Injection points are established by either modifying existing bridge components, such as the saddles or by designing purpose suited injection and exhaust collars, see figure 8.



Figure 8 Dehumidification plant and exhaust sleeve

5.2 *Sealing system*

We have carried out extensive research, development, workshop testing and on-site testing to determine the best systems for sealing the main cables, cable bands, saddles and other connected components. This has been supplemented by eight years of experience with sealing systems installed on bridges with dehumidification of main cables. We have concluded that the best system to seal the cable panels is the Cableguard™ Wrap System from the D.S. Brown Company. This is an elastomeric wrap with a thickness of 1.1 mm and a width of 200 mm. It is applied with slightly more than 50% overlap, so the total thickness is 2.2 mm. It is applied un-

der tension with a special wrapping machine. After wrapping a section it is heat bonded with a special heat blanket, which melts the two layers together and shrinks the material slightly, giving an even tighter fit. The wrapping and bonding work is illustrated below in figure 9. Special details have been developed to ensure sealing at the transition to the cable bands and to give a uniform appearance



Figure 9 Wrapping with wrapping machine and bonding with heat blankets

5.3 Control and monitoring system

The control and monitoring system allows remote control/adjustment of the system and data from the system documents that the system is performing properly and that the cables are protected from corrosion. Instrumentation is arranged at the dehumidification plant(s), in the buffer chamber(s) and at injection and exhaust points. Key data to be monitored includes system functionality, relative humidity, temperature, flow and pressure.

Generation of a number of standard and custom graphs should be integrated in the monitoring system allowing an even more effective overview of the systems functionality. One example of a valuable standard graph is the absolute water content in the injection air and exhaust air, which is calculated on the basis of the relative humidity and the temperature. This allows generation of a graph that clearly illustrates the drying out process with the ratio between the absolute water content for corresponding injection and exhaust points. Another valuable graph is a comparison of the corresponding injection and exhaust flows, which can indicate if any leakage is developing.

6 EXPERIENCE WITH SYSTEMS FOR MAIN CABLES AND LESSONS LEARNED

Extensive experience and valuable information concerning dehumidification systems for main cables has been obtained through numerous project designs, on site testing, full scale model testing and up till now 13 years of service. HSBE in Japan has opened and inspected the main cables of the Akashi-Kaikyo Bridge after 10 years of service in 2008. As mentioned in section 4.1 the wires were dry and the condition as at the time of construction, verifying that the dehumidification system is functioning well. From other bridges, such as the Little Belt Bridge in Denmark and the Högakusten Bridge in Sweden, the monitoring systems have during respectively 8 and 6 years confirmed the effectiveness of the systems.

6.1 Drying out process

The drying out process has been monitored on various bridges and it can vary greatly in time, depending on the type of cable, how much water is accumulated in the cables and the local climate. Generally it can be concluded that cables made up of strands dry out much quicker than cables of parallel wire. Strand cables have much larger voids and the water is easier to remove as the pathway from each void is more open than for parallel wire. On the Little Belt Bridge the strand cables were dry a few days after the dehumidification system was turned on. Earlier in-

spections had however shown that the cables were relatively dry, so this has also contributed to the short drying out period.

On the other end of the scale the parallel wire cables on the Högakusten Bridge took about 1.5 years to dry out. There are two reasons for this. Firstly the cables were very wet as the original sealing system had many defects. On the basis of data from the monitoring system it was calculated that roughly 500 liters of water were removed from a 300 m long stretch of the cable, corresponding to app. 3% of the void volume. Secondly the bridge is located in the far north, as far north as Alaska or Siberia, which means long freezing winters. Data from the monitoring system showed that the drying process progressed mainly in the summer, but during the winter much less drying out occurred due to the frozen condition of the water. This is illustrated by the graph in figure 10 where the ratio between the absolute moisture content in the exhaust air and injection air is shown. A high ratio indicates that a relatively large amount of water is being removed from the cables. When the ratio falls to one over the second summer no more water is being transported out of the cables, as they have become dry. Reports from Japan have indicated that a drying out period of roughly 3 months is more normal when the bridge is not located in such a cold climate and the cables are not so extremely wet.

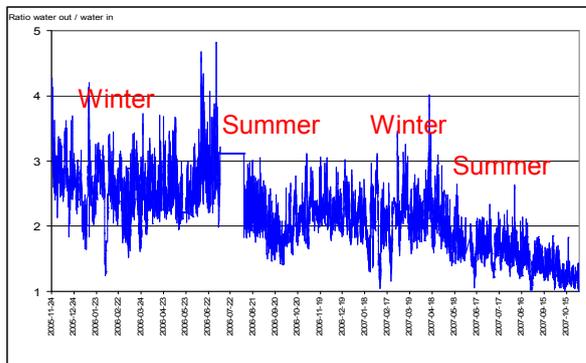


Figure 10 The drying out process on Högakusten Bridge, ratio of absolute water content

6.2 Sealing of cables

Data from the monitoring systems have also indicated that the sealing system described in section 5.2 is durable. The ratio between the exhaust flow and the injection flow is constantly monitored. This ratio is noted for each stretch of the main cable in connection with handing over the works. The current ratio is regularly compared with the original ratio and this has in all cases been constant, indicating that no leakage has developed.

Experience has shown that the elastomeric wrapping system described in section 5.2 seals the cables excellently. The wrapping work requires some initial training of the workers, but once they are trained and approved to do this work they have no problems meeting the quality requirements. The original heating blanket for bonding the two layers of elastomeric wrap has been improved in recent years. The original heating blanket was stiff and could not adapt to the shape of the main cable, which is usually not quite circular. This gave a less than 100% bond of the two layers, but still provided sufficient air tightness. The new heat blankets for the system are both flexible, so they adjust to the shape of the main cable, and inflatable, so they exert a uniform pressure during heating. The new heat blankets ensure a virtually 100% bond between the two layers.

Whereas the elastomeric wrapping system between the cable bands is quite standard and straightforward to apply, other details require more attention. These details include the transition between the wrapping system and the cable bands, the cable bands, saddle lids, shrouds and other encasings of the main cables.

The details of the face of the cable band towards the wrapping system vary from bridge to bridge, so there is not one solution that suits all bridges. The cable bands on some bridges have a groove in this position and it is possible to fit the elastomeric wrap into the groove and then caulk the groove to provide a good seal. On other bridges the bands have no groove and the wrap should be laid as flush with the band as possible. In this case a larger amount of caulk is

required to seal this detail and the void under the neoprene wedge should be completely filled. Furthermore, the two halves of the cable band have gaps in this face that have to be sealed. Usually there is a sufficiently wide gap, 1 - 2 cm wide, which provides enough room to seal with caulk. On some bridges the joint in the band is stair shaped and there is virtually no gap, which makes sealing difficult.

The cable bands have several details that require sealing. The large highly tensioned bolts that prevent the cable bands from slipping need to be sealed. Full scale tests have shown that leakage occurs at several positions on the bolts if they are not sealed, i.e. between the washer and the band, between the nut and the washer and along the threads of the bolt. All these positions must be sealed and several solutions can be applied. The whole area can be painted with a thick, durable paint system with good adhesion. Caulk can also be applied to prevent leakage. Both of these solutions require regular maintenance and must be removed and reapplied if the cable band bolts need re-tensioning. It is also possible to design and mount air tight caps that protect the bolts and minimize maintenance requirements, a prototype for the Hardanger Bridge is shown in figure 11.

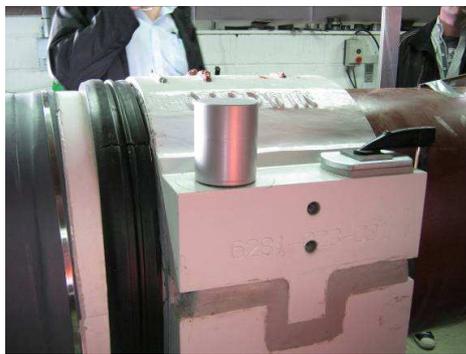


Figure 11 Prototype of sealing cap on cable band bolts

Experience from a number of bridges has led us to conclude that details that design engineers have believed were watertight are not at all watertight and are often one of the major sources of water ingress in main cables. This conclusion is also backed up by full scale testing that proves what type of detailing is necessary to provide air/water tightness. Our general conclusion is that all these types of details should be evaluated and replaced by proven watertight details in connection with a main cable dehumidification retrofit. These details include saddle lids, shrouds and other encasings of the main cables. The sealing system for these structural details should be twofold. The inner and main sealing should be of a flexible foam neoprene that is compressed and can effectively fill out and seal gaps of varying thickness, such as between the rough surface of a saddle and the saddle lid. The outer and secondary sealing should be of a durable, highly adhesive and UV-resistant caulk, which protects the inner seal from the elements as well as providing a double seal. All structural details should be designed to accommodate this double seal.



Figure 12 Shroud that is currently being replaced by a new airtight shroud

An illustrative example of the need for well designed sealing details is the transition shrouds adjacent to the anchorage chamber on the Högakusten Bridge see figure 12. These shrouds are placed adjacent to the exhaust points, where the overpressure from the dehumidification system is minimal and therefore more susceptible to water ingress. In the tendered project it was assumed that it was possible to sufficiently seal the existing shrouds, but experience has shown that this was not practical. One of the shrouds is currently being replaced after which the other three shrouds will follow later.

6.3 *Length of flow sections*

The maximum viable length of the flow sections is the key factor when starting design of a dehumidification system for main cables. The length is limited by the level of allowable pressure and the flow resistance of the actual cable. We generally recommend a maximum overpressure of roughly 2,000 Pa with regards to the durability of the sealing system and to limit leakage and power consumption. Main cables of parallel wire generally have a flow resistance of roughly 10 Pa/m. The resistance is affected by the condition of the wires and the level of the flow of the dry air. Wires that are in poor condition, i.e. high level of corrosion, will generally increase the resistance. A higher level of flow will also increase the resistance in a twofold manner, directly and indirectly. There is a direct theoretical relation between the flow and the level of resistance. In order to increase the flow it is also necessary to increase the pressure, which results in increased leakage and therefore additional resistance. The maximum recommended length of flow sections for parallel wire cables is generally about 200 m, depending on the actual resistance. Main cables made up of strands have a much lower flow resistance, roughly 1 Pa/m. Therefore it is possible to have much longer flow sections with strand cables.

In all cases the flow resistance should be measured during testing prior to design. If this is not possible or practical it can be done in connection with the works and the results incorporated in the final detailing of the system.

6.4 *Buffer chamber solution*

In 1995 we developed the buffer chamber solution in connection with dehumidification of the tower saddles on the Humber Bridge in England. There were problems with water ingress in the saddles and it was decided to dehumidify these as well as the main cables in the vicinity of the saddles. This would require constant injection of dry air in the saddles, as the dry air would flow into the main cables and eventually disappear through leaks in the existing sealing system. It would be relatively expensive in electrical consumption if the dehumidification unit was to run constantly, so the buffer chamber solution was developed. The air coming directly from the dehumidification unit has a very low relative humidity, just over 0%, which is much drier than necessary. Therefore a tower leg was utilized as a buffer chamber, where the air from the dehumidification unit is mixed up with ambient air to about 40% RH before injection in the saddles. In this manner the electrical consumption was significantly reduced, as well as wear on the dehumidification unit. This was also the first application of dehumidification on main cables, although the extent of the protection is not documented.

Following this successful application the buffer chamber solution has been integrated in all our main cable dehumidification projects. An existing structure is always utilized for the buffer chamber, as described in section 7. The volume of the available existing structures varies, so it has not in all cases been possible to have a chamber of optimal size. For example there are buffer chambers in the cross beams of the towers on the Högakusten Bridge, which provide a energy savings of roughly 50%. On the same bridge there is also a buffer chamber with a much larger volume arranged in part of the box girder, which gives an energy saving of roughly 75%. Optimally the buffer chamber should be large enough to give maximum savings in electrical consumption. The buffer chamber solution has a further advantage, as the dehumidification plant is protected from the elements when it is located inside the chamber, which minimizes maintenance requirements.

7 OPTIMIZING SYSTEMS INCLUDING INTEGRATED SYSTEMS

Optimising a system for main cables starts in the earliest design phase. At this time the layout of the main cables should be reviewed and a layout for the dehumidification system should be developed that suits well to the layout of the main cables. In the case of a new bridge, such as the above mentioned Messina, Hardanger, Lusail, and Hålogaland Bridges the design of the dehumidification system should be integrated in the design of the individual elements in close cooperation with the respective structural engineers. The design of the dehumidification system has interface to and influence on the design of most of the bridge elements, including the main cables, cable bands, saddles, cable shrouds, towers, bridge girder and the anchorage chambers. In the case of a new bridge it is also recommended to include full scale testing of critical sealing details, such as was done on the Hardanger Bridge, see figure 13. The wrapping system including details at cables bands, the tower saddles including adjacent transition shrouds, the cable bands and the transition shrouds at the anchor chamber were all tested and adjusted to achieve maximum sealing.

In the case of an existing bridge the bridge documents including drawings, specifications and reports from main cable inspections should be reviewed, summarised and incorporated in a preliminary design. On this basis a specific inspection should be planned and carried out and the results should also be incorporated in the design. Furthermore, the bridge operator's knowledge of the bridge should be fully utilised. The operator should be involved in the process by providing additional specific knowledge, providing local supplemental requirements and reviewing the preliminary design.



Figure 13 Full scale testing of sealing, left saddle and shroud, right cable band and transition at band

It is also advisable to carry out on site testing of the main cables on an existing bridge, as the features of every bridge are unique and resistance to the air flow varies according to cable type, cable diameter and cable condition. If there is any doubt as to whether voids in the cables have been filled during earlier works, the ability to inject air and cause it to flow the length of the cables should also be tested. The tests can also provide valuable information about the current sealing of the cables and how much supplemental sealing will be required. Such tests have been carried out on a number of existing bridges. Pictures illustrating trial injection on the Älvsborg Bridge are shown in fig. 14.



Figure 14 Injection and flow testing at tower saddle and mid span on the Älvsborg Bridge, Sweden

The layout for the main cable dehumidification system comprises the placement of the injection and exhaust points, flow directions and lengths, the placement of buffer chamber(s) and dehumidification plant(s) and ducting connecting the buffer chamber(s) with the injection points.

The lengths of main cables in the main and side spans (and back spans if these are found) and the type of main cable (parallel wire or strand and the diameter) are dictating for the placement of the injection and exhaust points. As described in section 6 it is possible to work with much longer flow stretches for main cables of strands than main cables of parallel wire. The flow stretches should be as long as possible to minimise the amount of equipment, but at the same time respect the maximum length.

The buffer chamber(s) including the dehumidification plant(s) should be placed inside an existing structure if possible, as this will save the cost of constructing a chamber. If the bridge girder is a box girder it is very convenient to isolate an area of this structure and utilise it as a buffer chamber. A part of an anchor chamber can also be utilised as a buffer chamber, though this will usually require constructing at least two walls to isolate a portion of the chamber. As mentioned in section 6.4, the volume of the buffer chamber must be sufficiently large in order to obtain the full effect and maximise energy savings.

Depending on the design of the bridge it might be relevant to apply an integrated system, i.e. a system that dehumidifies and protects two or more bridge elements. An integrated system is the ultimate of optimisation, as one set of equipment protects two or more structural elements, resulting in minimal construction, operation and maintenance costs, i.e. lowest life cycle cost. A dehumidification system for main cables can be integrated with protection of one or more of the following elements: steel box girder, closed steel towers and anchor chambers. Systems have already been designed that cover all these structural elements. Examples of integrated systems are further described below in section 7.2.

7.1 Optimization criteria

Depending on the layout of the main cables and if an integrated system is relevant, it may be possible to develop a number of alternative layouts for the dehumidification system. In order to evaluate the optimal system we have developed the following criteria to evaluate and compare the individual layouts. These criteria can also be used to further optimise the chosen layout.

- Feasibility – The layout must be within the limits described in this paper.
- Construction cost – A layout that has less equipment and requires less construction work will have a lower price.
- Maintenance friendliness - Equipment should be easy to access and easy to maintain.
- Maintenance costs - Maintenance costs are minimized by maintenance friendliness, a minimal amount of equipment to maintain and placement of equipment in the protected environment of a buffer chamber.
- Operation costs – Operation costs are minimized by using as few dehumidification plants as possible, plants with as little equipment as possible and a suitably large size of buffer chambers. These will all reduce power consumption.
- Necessary overpressure to force dry air through all the flow stretches - The overpressure should be below app. 2,000 Pa (0.3 psi) so as not to overload the sealing system and to minimize leakage.
- Monitoring – It should be possible to fully monitor the system's functionality and the durability of the sealing.
- Aesthetics - The bridge's appearance should not be not disturbed. This is achieved by utilizing a minimal amount of visible equipment and slender elements that are hardly visible.
- Individual bridge requirements – There may be other requirements on the actual bridge that have influence on the dehumidification system. These should be discussed and determined in cooperation with the bridge owner/operator.

7.2 Examples of integrated dehumidification systems

The following three examples of the Hardanger Bridge in Norway, the Älvsborg Bridge in Sweden and the Lusail Bridges in Qatar illustrate some of the possibilities for integrated dehumidification systems, especially the Lusail Bridges, as they have a fully integrated system.

A retrofit of the 44 year old Älvsborg Bridge in Gothenburg, Sweden is currently under construction. The main cables are made up of helical strands and the strands are only coated with paint, i.e. no galvanisation. An in-depth inspection of the main cables in 2005 showed serious corrosion on the bottom of the lower strands, though with negligible reduction of the load carrying capacity. The corrosion protection of the main cables needed rehabilitation and a design study was carried out to determine the optimal method of rehabilitation. Dehumidification was chosen, as the study concluded that it was superior in all aspects.

The integrated system encompasses the main cables and the strands in the anchorage chambers. Part of the southern anchor house is enclosed as a buffer chamber and a dehumidification plant that serves the entire system is located here. Ducting connects the buffer chamber with injection points at the middle of the main span. Dry air flows through the main cables about 400 m in both directions and finally flows through the anchorage chambers. At the southern end the dry air returns to the buffer chamber and is re-circulated, giving a highly effective system.

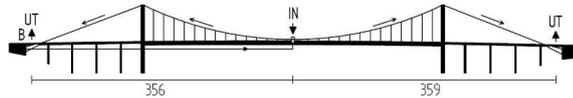


Figure 15 Älvsborg Bridge in Sweden and layout of dehumidification system

The Hardanger Bridge in Norway is currently under construction (completion in 2012) and has a main span of 1,310 m, see figure 6. The stiffening bridge girder is a steel box girder and the main cables are made up of parallel wires. The two dehumidification plants in the box girder protect the inner surface of the box girder and utilise the volume as a buffer chamber for provision of dry air to the main cables. Ducts run up through the towers to injection points at the saddles and along two of the shorter suspender cables to injection points on the main cables. In this manner one integrated dehumidification system protects the box girder and the main cables. A separate system provides for each anchorage chamber, as it was not feasible to integrate them in the system.



Figure 16 The Lusail Bridges in Qatar

Construction of the twin Lusail suspension bridges in Qatar is commencing with a fully integrated dehumidification system, see figure 16. The inner surfaces of all steel elements are protected from corrosion by one integrated system with just one dehumidification plant. The bridges each have two steel box girders, a circular steel tower and main cables made of strands. A dehumidification plant is located in one box girder and it produces dry air and blows it through one box girder, then through a duct at the end of the bridge connecting the two box girders, through the other box girder and finally back to the plant through a duct at the other end of the bridge. The entire collective volume of the box girders serves as a buffer chamber.

Part of the dry air in the box girders is injected into the tower from one side and circulates through the tower to the opposite box girder. The air in the tower is slightly over pressured, which causes a controlled amount of air to flow through the main cables, where it finally flows out through the anchor chambers. In this manner the insides of the box girders and the towers, the main cables and the cable strands in the anchorages are all protected from corrosion by just one integrated system. This is a fully optimised and extremely economical system.

8 CONCLUSION

International experience from USA, Japan and Europe has proven that corrosion of suspension bridge main cables is a very serious problem that can lead to reduction of load carrying capacity or even closure of the bridge. The degree of corrosion is generally worst on old bridges, but even some relatively young bridges between 5 and 30 years of age have been shown to have serious corrosion problems. As there are so many corrosion problems with main cables it is an obvious conclusion that the earlier applied traditional protection systems do not provide sufficient protection. All suspension bridge owners/operators should instigate measures to inspect and evaluate their main cables and upgrade the corrosion protection to the only system that actually prevents corrosion - dehumidification, such as described in this paper. A dehumidification system controls the atmosphere inside the cables and keeps the relative humidity below the critical level of 40%.

There are currently dehumidification systems for main cables in service on 21 suspension bridges in a total of 8 different countries with up to 13 years of service. Furthermore, there are currently at least 6 different projects commencing in 4 different countries, which gives a total of at least 27 systems in 11 different countries. The technology is well proven and developed and should be applied to all suspension bridge main cables. When designing dehumidification systems for main cables the experience and guidelines laid out in this paper should be utilized.

REFERENCES

- Bloomstine, Matthew L. et al, 2010, Dehumidification of Suspension Bridge Main Cables, *The 5th International Conference on Bridge Maintenance, Safety and Management (IABMAS)*, Philadelphia, USA.
- Bloomstine, Matthew L. et al, 2008, The Högakusten Bridge – Corrosion Protection of the Main Cables and Maintenance of Major Components, *6th International Cable Supported Bridge Operators' Conference*, Takamatsu, Japan
- Bloomstine, Matthew L. et al, 2006, Prevention of Main Cable Corrosion by Dehumidification, *5th International Cable Supported Bridge Operators' Conference*, New York, USA.
- Bloomstine, Matthew L. et al, 2006, Main Cable Corrosion Protection by Dehumidification, *IABSE Conference on Operation, Maintenance and Rehabilitation of Large Infrastructure Projects, Bridges and Tunnels*, Copenhagen, Denmark.
- Bloomstine, Matthew L. et al, 2005, State-of-the-Art Main Cable Corrosion Protection by Dehumidification, *3rd New York City Bridge Conference*, New York, USA.
- Bloomstine, Matthew L. et al, 2004, Little Belt Suspension Bridge - Corrosion Protection of Main Cables and Maintenance of Major Components, *4th International Cable Supported Bridge Operators' Conference*, Copenhagen, Denmark.
- Bloomstine, Matthew L. et al, 1999, Corrosion Protection by Means of Dehumidification *IABSE Symposium, Structures of the Future – The Search for Quality*, Rio de Janeiro, Brazil.
- Furuya, Kazuhiko et al, 2000, Corrosion Mechanisms and Protection Methods for Suspension Bridge Cables, *Structural Engineering International 3/2000*, 189-193
- Honshu-Shikoku Bridge Expressway Company Ltd., The Akashi Kaikyo Bridge: Verification of Rustproof on the Cables by the Dry Air Injection System, *Newsletter on Long-Span Bridges No. 38, July 2009*
- Reina, Peter, 2007, British Engineers Tackle Corroded Cables on Trio, *enr.construction.com*, 4/11/2007