Inspection Protocol and Non-destructive Method Selection for Precast Bridges

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ABSTRACT; *Precast concrete box girder bridges are susceptible to collapse and failure due to corrosion and fracture of prestresssing strands in the bottom flange of the girder. Inspection protocols using NDE methods has the potential to identify the presence of corroded prestressing strands, which can prevent collapse of these concrete bridges due to corrosion and fracture of prestressing strands. Two NDE methods have been chosen to be part of the inspection protocol for precast concrete box girder bridges. Infrared (IR) thermography, through the use of cameras, can identify areas of infrared radiation emitted from the surfaces of objects, which in turn can be related to surface temperatures. The differences in surface temperatures assist in identification of areas of delamination and presence of cracks on the bottom flange of the box girder. The areas of delamination can result from prestressing strands that have section loss caused by corrosion. If large areas of delamination are identified, then Magnetic Flux Leakage (MFL) can be used on the areas identified as having delamination. MFL can provide data on the section loss of prestressing strands that result from corrosion. A cost estimate has been established for performing both IR Thermography and MFL, which each are part of the inspection protocol. An inspection protocol and its associated costs and limitations to perform NDE methods on precast concrete box girder bridges is presented to prevent these bridges from failing due to corrosion and fracture of prestressing strands.*

Keywords: precast concrete, non-destructive evaluation, infrared thermography, magnetic flux leakage

INTRODUCTION

Corrosion of prestressing steel in concrete bridge has been known to be a primary source of deterioration in the Lake View Drive Bridge problem. The problem could introduce consequences in prestressed structures where the steel is normally under relatively high tensile stresses. Relative small losses of cross section of steel element due to corrosion could cause abrupt fracture resulting in major damage to bridge structure or its collapse.

The early detection of corrosion damage in reinforced concrete is challenging because the steel bars are embedded in the concrete, and inaccessible for visual inspection. The structure may already be seriously compromised when typical manifestations of corrosion distress become evident (e.g., stains on the concrete surface, delamination and cracking).

Nondestructive evaluation (NDE) techniques are increasingly being considered for the condition assessment of corrosion damage in concrete bridge. Each of the NDE techniques has its own advantages and disadvantaged. Combining several methods may yield better results by taking advantage of the efficiencies of individual techniques. The ideal NDE techniques must be able to detect reliably the smallest size flaw that is of concern, and must be able to inspect large areas as well as localized areas. Further, it must be efficient in term of labor and equipment, non obstructive to the surrounding environment, and convenient to the users of the structure [1].

The goal of the study is to determine accurate and reliable assessment of corrosion damage in concrete bridge. The objectives of the study are to develop a rationale NDE technique based on application of the principle of Infrared (IR) thermography and Magnetic Flux Leakage (MFL) to detect corrosion of the embedded reinforcement steel in concrete bridge; to develop an overall inspection protocol for these techniques; and to develop an estimate of equipment and implementation costs by using these techniques.

APPLICATION OF THE PRINCIPLE OF INFRARED (IR) THERMOGRAPHY IN CONCRETE BRIDGE

IR thermography utilizes cameras that determine infrared radiation emitted from the surfaces of objects, which in turn can be related to surface temperatures. Information about the subsurface can be inferred from the surface temperature because the heat flow through the object is affected by the presence of internal flaws [2]. The rate of energy emitted per unit surface area depends on the temperature and emissivity of the material according to Stefan-Boltzmann Equation

$$Q = \varepsilon\sigma T^4$$

where Q is total radiant emission of the surface (W/m^2); ε is emissivity of the test object, which is defined as the ability of the test object to radiate energy compared to a perfect black body radiator (unitless); σ is Stefan-Boltzmann constant (5.67×10^{-8} $W/m^2/K^4$); and T is absolute temperature of the object (K) [3].

Maldague investigated the potential of thermography with regard to NDE of concrete [3]. The results show that the deeper defects will be detected at a later time with a reduced contrast, where observation time is a function of the square of the depth, as shown in this equation

$$t \sim \frac{z^2}{\alpha}$$

where t is observation time; z is depth of the target and; α is thermal diffusivity of the material which is defined as

$$\alpha = \frac{k}{\rho c}$$

where k is thermal conductivity; ρ is density and; c is specific heat.

Also it was suggested that there was a relationship between the loss of contrast which occurs at increasing depths, where the loss of thermal contrast is proportional to the cube of the depth, as shown in this equation:

$$c \sim \frac{1}{z^3}$$

where c is thermal contrast loss due to defect depth and z is depth of the target [3].

IR thermography is generally used to detect cracks, delaminations, and disintegration in bridge (ASTM D4788). The advantages of this method are the low risk involved in the use of equipment and the speed of inspection (including night inspections). Because of the large coverage of the cameras, this method can also identify the horizontal extent of large defects. The disadvantages of this method include the effects of the environment on the surface temperatures and the emissivity factor [2].

APPLICATION OF THE PRINCIPLE OF MAGNETIC FLUX LEAKAGE (MFL) TO DETECT CORROSION of PRESTRESSING STEEL IN CONCRETE BRIDGE

The magnetic based NDE concept for assessing the condition of steel in concrete structure utilizes the ferromagnetic property of the steel to detect perturbances of an externally applied magnetic field due to presence of flaws in steel. For magnetic field strength below saturation, the following relationship holds:

$$B = \mu \, H$$

where B is total magnetic flux density, Wb/m^2 (or Tesla); μ is material magnetic permeability, Wb/Am (or H/m); and H is magnetic field strength or intensity, A/m.

Some of atomic diapoles of reinforcing steel become aligned with the field and the steel becomes magnetized when an external magnetic field with sufficient strength field is applied near a reinforced concrete. The effect of concrete on the magnetic field is insignificant. When the strength of the externally applied field is adequately large, complete alignment of the atomic dipoles will result which is known as magnetic saturation of the steel. Additional field strength beyond the level causing saturation will have no influence on the magnetization of the steel. If the direction of the applied magnetic field is set to collinear with the longitudinal reinforcing steel, the flux lines will also be collinear with the steel elements within the concrete. Any change in the cross sectional area of the steel at any point will cause a flux leakage, where the continuous flux lines within the steel will forced into the medium surrounding the flaw [4].

Hall probe detection devices are used in the vicinity of the flaw to measure and record the perturbance of the magnetic field as an electrical charge. If the magnetic source and sensors are moved along the length of the concrete member, the signature is then recorded as a continuous signal that can be analyzed to obtain information relevant to the location and extent of the flaw. Signal features such as the amplitude (A) and peak to peak separation (p), as shown in the Figure 1, are used to characterize them [4].

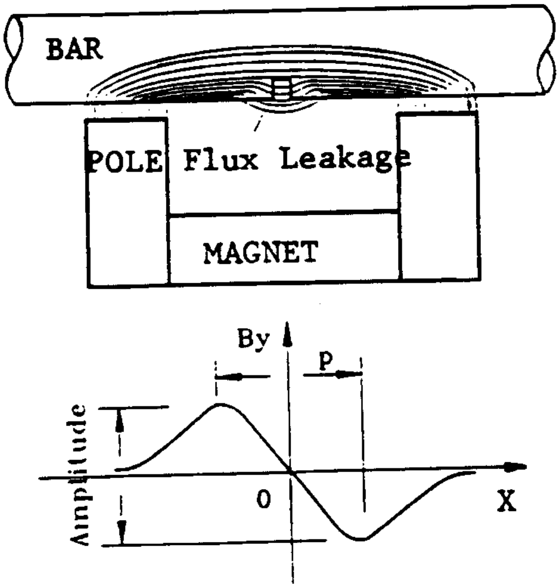

FIGURE 1 Magnetic flux leakage and signal [4].

Ghorbanpoor developed study about non-destructive testing system based on the magnetic flux leakage principle that would allow assessment of the condition of reinforcing and prestressing steels in concrete bridge. The effects of the flaw size and distance between the flaw and the magnetic source/sensor are the most significant factor that influences the magnetic signals. The theoretical solution available for a simplified case of the spherical void embedded in a ferromagnetic medium shows that the amplitude of the magnetic variation signatures proportionate directly to the flaw volume and inversely to the cube of the distance between the flaw and the source/sensor as given as [5]

$$A = (0.8587)\mu H\left(\frac{\mu_0 - \mu}{\mu_0 + 2\mu}\right)\frac{a^3}{d^3}$$

where A is amplitude of magnetic variation signature at a flaw; μ_0 is magnetic permeability of free space (air), 4π x 10^{-7} (H/m); a is flaw size, d is distance between flaw and point of interest (location of source/sensor).

The MFL concept showed excellent potential for use as an NDE tool for detection of corrosion of steel in concrete members. This determination was based on the results of extensive laboratory and field testing of prestressed concrete members. Test specimens with mechanically induced flaws, such as cutout cross-sectional areas, and with real corrosion from accelerated corrosion tests were also used in the study. It was shown that the MFL technique could detect flaws in prestressing steel equivalent to a 5–10 percent loss of cross-section [4].

INSPECTION PROTOCOL RATIONALE

The purpose of these non-destructive evaluation techniques is to ensure the safety of a bridge. For bridges such as the Lake View Drive Bridge, the critical issue is the collapse of one or more girders. Because collapse of this bridge was primarily a function of corrosion in the prestressed strands, detection of corrosion within a concrete housing is the objective of non-destructive evaluation in these bridges.

In response to the Lake View Drive bridge collapse, PennDOT released updated inspection coding, updated inspection protocol and load posting recommendations. In the case of inspection coding, PennDOT suggested condition ratings on a 1 – 10 qualitative scale, based on visual inspection. For inspection protocol, PennDOT declared that a bridges rating would be based on the weakest member, so if one section of the bridge receives a 3 rating, the same rating applies to the whole bridge. These updated qualifications do not suggest any evaluation technology, but rather more carefully categorize information received by visual inspection [7]. Because visual inspection is a particularly weak technique for inspecting corrosion within concrete, non-destructive evaluation techniques will be beneficial.

A number of challenges arise which make corrosion detection in concrete an inexact science. The first and most obvious challenge is that the steel in question is embedded within concrete. This hinders visual inspection as well as the use of many technologies because they cannot approach the steel directly; the techniques must first non-destructively penetrate the layer of concrete. Another issue is that there is no useful technique which can directly measure corrosion through concrete. The best available techniques can measure section loss due to corrosion, but cannot detect corrosion itself. Unfortunately, many variables disturb section loss detection such as coverage, variable strand thickness, or the presence of other steel elements such as chairs or webbing.

Rationale of Infrared Thermography

Although infrared thermography is an even more indirect method of corrosion detection, it can indicate areas which are highly susceptible. Recall that corrosion occurs in the presence of air and water. While the concrete cover protects from these elements, it's alkaline composition acts as a protective layer, further protecting the steel from corrosion. Thus, areas where the concrete is separated from the steel (delaminations) will be most susceptible to corrosion. This is precisely what infrared cameras are intended to detect.

Because of the low cost of the camera, low labor costs and lack of traffic restrictions, infrared thermography is beneficial as a preliminary technique. Technicians can take accurate photographs of several bridges per day, and this could even be done alongside routine bi-annual inspections. The infrared photographs can then be analyzed and risk can be addressed. For bridges with low delaminations, everything else being equal, the bridges can stay on the two year inspection cycle. For bridges with heavy or large delaminated areas, they can either be put on a more frequent inspection cycle, or can be re-inspected using more localized non-destructive evaluation techniques.

Rationale of Magnetic Flux Leakage

Coupled with an infrared camera, magnetic flux leakage will be able to accurately address the biggest issue of high-risk concrete box-beam bridges. Though more expensive than infrared thermograpy, this technique is intended to directly detect section loss due to corrosion. The bridge deck must be closed to traffic, and where necessary, traffic below the bridge. Furthermore, at least four technicians will need to be present and either scaffolding or a truck mounted gantries will be needed to get the technicians comfortably standing underneath the bridge deck.

Magnetic Flux Leakage Issues

Two main issues have been raised with the use of magnetic flux leakage. The first issue is one of detection of corrosion using this method. The concrete cover underneath the strands is typically not uniform in construction, and can be even worse when in service due to delaminations or spalled concrete. This is problematic because since the technique depends in variations in cross-sectional strand area, variations in concrete cover can make results ambiguous. However, we argue that concrete cover will vary continuously and predictably compared to quickly sloping section loss, or point-like cracking. In the readout, the change in signal from section loss will be a noticeably higher peak than the change in signal due to changing concrete cover.

Mounting is another issue associated with using magnetic flux leakage in bridge inspection. Magnetic flux leakage detection devices are typically heavy, making it difficult for a technician to lift and place uniformly on the underside of a bridge. This may also generate a safety issue, because the technicians are tens of feet off of the ground. One solution could be a type of mounting system which connects to the deck of the bridge, so that the whole bridge could be scanned. Though this would be most comprehensive in bridge inspection, the apparatus could be quite expensive and portability may be an issue as well. Also a similar apparatus could entail mounting the MFL device onto an aluminum frame with rollers which allow the MFL device to be moved perpendicular to the box girder spans to specified locations. The aluminum frame would rest on two gantries, one of each edge of the box girder spans. The MFL device could then be moved in the plane of the girder span with the movement of the truck mounted gantry down the span of the bridge. All the equipment necessary for performing MFL would be in the gantries. Another solution to the weight of the apparatus could be in the design of the apparatus itself. Perhaps it could be designed such that much of the equipment could be set next to the technician's feet and cables connected to the MFL magnets would hold the device in place near the concrete surface on the bottom of the box girder. The cables would be connected to points on the sides or top of the bridge. This would allow an inspector to use a truck mounted gantry and will some effort place the MFL device completely against the concrete surface.

COST ESTIMATE FOR INSPECTION PROTOCOL

The inspection protocol mentions the use of IR thermography to determine if a bridge shows signs of delamination. Table 1 includes an estimated cost of the IR camera, labor for one personnel to take IR Thermography images of them box girder bridge, labor for an engineer or technician to review the images and determine areas of possible delamination. Also the engineer will determine if further NDE testing is necessary, such as MFL, and develop a plan of what areas need to be tested with MFL. The estimated costs in Table 1 represent the IR thermography inspection taking place at the time as the normal bridge inspection cycle, such as every two years. The cost for the IR thermography camera is distributed by an assumed number of bridge inspections per year, which provides a cost of the camera per bridge inspection. The total estimated inspection cost of $3,500 is for one bridge inspection using IR thermography.

TABLE 1 IR Thermography Inspection Cost.

	Cost	hours	number of bridges per 1 year cycle	cost/bridge
IR Thermography Camera	$50,000		100	$500
IR Thermography Operator	$100/hr	4		$400
Field Engineer	$100/hr	24		$2,400
Truck and Misc. Expenses	$200			$200
Total Inspection Cost				**$3,500**

The decision of the engineer to further NDE test the precast, prestressed box girder bridge leads to the use of MFL testing. The cost for MFL testing is much more labor intensive and expensive because of having to physically be on or near the bridge to perform MFL testing. Also the cost of traffic control and other miscellaneous costs associated with performing bridge inspections and closure of traffic lanes, both on the bridge and on occasions the traffic lanes underneath the bridge. The costs in Table 1 did not bear these costs because the IR thermography was being performed during a routine bridge inspection and also the IR thermography does not require traffic control because the IR thermography images can be taken from a distance away from the bridge and out of the lanes of traffic. Table 2 is a compilation of MFL instrumentation and equipment costs, bridge inspector labor, engineer labor, traffic control, police detail cost, and cost of a truck mounted gantry estimated to cost approximately $23,800. The inspection will take two days and require the possible use of two truck mounted gantries perform the MFL testing. A minimum of two personnel per gantry and police detail for possible closure of lanes on the bridge and the lanes below the bridge is required. The cost of the MFL device and the associated equipment costs is divided by an estimate of twenty-five bridges a year requiring MFL testing, which provides a cost per bridge inspection estimate for these items. The engineer will need to analyze the MFL data, determine the degree of section loss in the prestressed strands, and develop bridge closure, load restriction and lane restriction plans if an inspected bridge requires one of these actions. The IR Thermography and MFL testing together should be performed at least once a year on bridges of concern, such as twenty five percent section loss of prestressing strands in the bottom flanges of a prestressed concrete box girder bridge.

TABLE 2 MFL Inspection Cost.

	Cost	hours	number of bridges per 1 year cycle	cost/bridge
Magnetic Flux Leakage (MFL) Instrument	$15,000		25	$600
MFL data acquisition (software, computer, etc.)	$9,000		25	$360
MFL Apparatus	$20,000		25	$800
Truck Mounted Gantries	$200/hr	16		3200
Bridge Inspector	$100/hr	16		$1,600
Bridge Inspector	$100/hr	16		$1,600
Bridge Inspector	$100/hr	16		$1,600
Bridge Inspector	$100/hr	16		$1,600
Police Detail	$25/hr	16		$1,600
Police Detail	$25/hr	16		$1,600
Traffic Control	$375/hr	16		$6,000
Field Engineer	$100/hr	24		$2,400
Truck and Misc. Expenses	$800			$800
Total Inspection Cost				**$23,760**

CONCLUSION

Bridge inspection protocol utilizing the NDE methods of infrared thermography and magnetic flux leakage allow bridge engineers to identify possible corrosion of prestressed strands in prestressed box girder bridges, which can lead to collapse of these types of bridges. IR thermography provides inspectors a cost effective method to identify delamination areas and cracks in the bridge, while performing routine bridge inspections. Large areas of delamination can possibly be caused by corrosion of prestressed strands. If the bridge engineer suspects that problematic section loss of prestressing strands might be present in the bottom flange of the concrete box girders, more involved and expensive MFL testing can be performed. The MFL testing indicates possible section loss of the prestressing strands and provides the engineer a percentage of strand section loss existing in the bridge. Analysis of the MFL testing data could lead to decisions to close, lane restrict, or load restrict a given bridge.

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