WARRANTING QUALITY OF STEEL BRIDGE COATING

By Luh M. Chang,[1] Maged E. Georgy,[2] and Yassir A. AbdelRazig[3]

ABSTRACT: Civil infrastructure systems, particularly the highway and bridge systems, have become a focal point of attention both nationally and among researchers. Because many of the nation's bridges have been identified by the Federal Highway Administration as deficient, more attention needs to be given to the quality of bridge coatings, which act as inhibitors of bridge deterioration. This paper represents an extended study by the authors to establish and implement contract warranties for steel bridge coatings. First, the earlier activities in warranting the quality of bridge coatings are reviewed. Next, the writers focus on the basic categories of a steel bridge coating warranty, especially the warranty period and defects for which the contractor is held responsible. The paper further illustrates the functioning of a hybrid model for nondestructive quality assessment of steel bridge coatings. The model provides objective and quantitative analysis to improve the coating quality assessment process. This approach prevents potential conflicts that might arise between the state Department of Transportation and the bridge-coating contractors during the warranty implementation.

INTRODUCTION

The aging U.S. civil infrastructure systems have gained increasing attention in recent years, both on a national level and among researchers. Huge investments are allocated every year for the replacement, rehabilitation, and maintenance of these systems. A significant portion of the investments is in the highway transportation and bridge systems, which constitute critical links for the entire nation's infrastructure (Aktan et al. 1996). Historic levels of transportation investments—over $50 billion—are proposed for the fiscal year 2000. Of this number, almost 60% are allocated to the Federal Highway Administration (FHWA) (*FY2000* 1999).

A study by the FHWA in the early 1990s stated that about 40% of the national highway bridges were deemed deficient (Dunker and Rabbat 1995). Bridge deficiencies can be classified as either structural deficiencies or functional obsolescence. Structurally deficient bridges are those that have been closed or require immediate rehabilitation to remain operational. Functionally obsolete bridges are those whose deck geometry, load-carrying capacity, clearance, or approach roadway alignment no longer meet the transportation system requirements (Dunker and Rabbat 1995).

Deterioration of a bridge condition leading to the label ''structurally deficient'' primarily arises from corrosive action upon the steel bridge components (*Good* 1989a). The progressive corrosive action reduces the cross section of the steel members and subsequently reduces the bridge's loading capacity. Although several alternatives exist for coating a steel bridge surface, thus isolating it from the surrounding environment, metallic paints are the more commonly used. They function as inhibitors or barriers to prevent, as much as possible, corrosive attack upon the steel substrate of moisture, high-salt-content air, and oxidizing chemicals (*Good* 1989a). To establish a successful bridge coating system, the following conditions need to be satisfied:

1. To choose a suitable and durable coating system that endures the severe attacks of the environment
2. To control the application of such a coating system
3. To warrant the coating system to remain in an acceptable condition until the following maintenance/rehabilitation activities are sought

After specifying a suitable system to coat the bridge substrate, the responsibility falls primarily on the contractor for the successful application of the selected system. Project acceptance is deemed to be a critical milestone in the legal relationship between the owner, that is, Department of Transportation (DOT), and the bridge-coating contractor. Without explicit and unambiguous contract wording to warrant the materials and workmanship after the substantial completion of the project, it becomes difficult to place further responsibility on the contractor if the work is later found to be deficient. Meanwhile, the use of contract warranties shifts the responsibility for the system performance to the contractor for a specified period of time after the substantial completion of all contract work.

In the last few years, the cost of maintaining and rehabilitating steel bridges using existing coating systems has risen dramatically (Tam and Stiemer 1996). This increase can be attributed to the stricter environmental constraints banning high volatile organic compounds (VOC) in the coating systems used. Also, stricter requirements for containment, worker safety, and debris disposal have been widely established. Ironically, a number of state DOTs are experiencing a decline in the quality of contractors' workmanship. With the limited budgets for the statewide maintenance activity of steel bridges, state DOTs face the dilemma of whether to repair the deficiencies or to leave the bridge without recovery until the next scheduled maintenance/rehabilitation activity takes place. The former choice would result in an increase in the actual maintenance cost, while the latter would shorten the expected service life of the structure.

The absence of contract warranties hypothetically eliminates the contractor's accountability for future defects in his or her work. This imposes a challenge to the establishment of a successful bridge coating system. The declining quality that has been experienced by some DOTs regarding the newly coated steel bridges calls for a broader examination of using contract warranties, which will help offset the decline in quality while simultaneously systematizing the bridge-coating practices.

BACKGROUND

Hare (1990) reported that one- or two-year guarantees were not uncommon in bridge-coating specifications in the United States, although the guarantees were often vague and poorly

[1]Assoc. Prof., Div. of Constr. Engrg. and Mgmt., School of Civ. Engrg., Purdue Univ., West Lafayette, IN 47907-1294. E-mail: changlm@ecn.purdue.edu

[2]PhD Candidate, Div. of Constr. Engrg. and Mgmt., School of Civ. Engrg., Purdue Univ., West Lafayette, IN. E-mail: georgy@ecn.purdue.edu

[3]Asst. Prof., Dept. of Civ. Engrg., Florida A&M—Florida State Univ., Tallahassee, FL 32310-6046. E-mail: abdelraz@eng.fsu.edu

Note. Discussion open until March 1, 2001. To extend the closing date one month, a written request must be filed with the ASCE Manager of Journals. The manuscript for this paper was submitted for review and possible publication on February 18, 2000. This paper is part of the ***Journal of Construction Engineering and Management***, Vol. 126, No. 5, September/October, 2000. ©ASCE, ISSN 0733-9634/00/0005-0374–0380/$8.00 + $.50 per page. Paper No. 22181.

J. Constr. Eng. Manage., 2000, 126(5): 374-380

written. One of the earlier organized efforts to investigate the use of highway warranties was pursued in 1987 when the Transportation Research Board, with FHWA cooperation, initiated a task force to identify innovative highway contracting practices (Hancher 1994). Several experimental projects using warranties were approved. One of the experimental projects in Michigan used contract clauses to warrant the steel bridge coating for a two-year period.

In 1995, the FHWA investigated European practices as they relate to steel bridge coatings (FHWA 1997). The study covers practices in Switzerland, Germany, The Netherlands, and the United Kingdom. Based on the experiences shared by representatives of the European highway industry, six areas were highlighted for further consideration by the U.S. highway industry, including the use of contract warranties for steel bridge coating projects (FHWA 1997; ''U.S.'' 1998).

According to a recent survey by Russell et al. (1999), the number of state DOTs using warranties has continued to increase since the 1991 Intermodal Surface Transportation Efficiency Act allowed the use of warranty contracting on projects that are part of the national highway system. A noticeable surge in warranty use has taken place over the last three years. According to the survey, at least 240 highway warranty projects have been completed since 1987. Bridge painting has been cited in the study as the prime end product currently being warranted. Bridge painting projects where warranties have been used account for 52% of the total number of warranted projects. Furthermore, Michigan DOT has required the warranting of all its steel bridge painting projects since 1996 (Russell et al. 1999).

DEVELOPING WARRANTIES FOR STEEL BRIDGE COATING PROJECTS

Since 1996, the writers have participated in an extended study to develop and implement steel bridge warranties for Indiana DOT. General practice reviews revealed a growing interest in using highway warranties. The warranty clauses used by a number of DOTs for warranting their steel bridge coatings show several similarities in structure and content. A two year warranty period is dominant for the examined clauses. The warranties show no distinction in the warranty period for alternate weather and environmental conditions. Defects covered by the warranties include rusting, peeling, blistering, insufficient coating thickness, and coating damage caused by workers, among others. The recognition of defects is the duty of the engineer as defined by these warranties. This is accomplished through visual inspection and dry film thickness measurements. Only the decision regarding the film thickness is unambiguous; no measurement procedures or standards are given for the recognition of the visible defects. Supplemental performance and lien bonds are usually required to back the contractor's commitment throughout the warranty period.

The comprehensive analysis led to identifying 10 categories that are basic to establishing a warranty form for steel bridge coatings. The 10 categories are

1. *Warranty period*: This category addresses the period following the completion of the contract works during which the contractor is held responsible for the quality of the bridge coating.
2. *Defects identification*: This category addresses the defects that arise from poor materials and/or workmanship and the limits beyond which the contractor will be considered accountable for defective contract works.
3. *Inspection schedule*: This category addresses the procedure and timing of the bridge coating inspection that takes place during the warranty period.
4. *Repair procedure and progress schedule for corrective works*: This category addresses the submittal and approval of the repair procedures and the schedule the contractor will follow in carrying out any corrective work.
5. *Season of work*: This category addresses the suitability of the weather conditions as well as the DOT's timing preference for carrying out the corrective work.
6. *Liability insurance*: This category deals with the legal liability to the public.
7. *Traffic control*: This category addresses the procedures and requirements set by the DOT for controlling the traffic flow during the corrective work period.
8. *Supplementary performance and lien bonds*: This category addresses the issuance of bonds that insure the DOT against contingencies such as quality of the corrective work and payables owed to the labor, equipment, and materials used throughout the corrective work period.
9. *Surety company*: This category addresses the entity that guarantees the proper execution of all corrective works to the satisfaction of the DOT.
10. *Work permits*: This category addresses the various permits the contractor must obtain in order to proceed with the corrective work.

The 10 categories can be classified as either technical or procedural. Except for the first two categories, warranty period and defects identification, the remaining categories are mostly procedural in nature. As the procedural categories can differ in accordance with the administrative practices of each DOT, the paper will focus on the warranty period and defects identification categories. These two categories remain among the most important elements in establishing a successful warranty for steel bridge coatings. Further details can be found in other publications by the writers (Chang and Georgy 1999).

Warranty Period

Warranties are introduced to warrant the quality of contract work for a certain period of time following the substantial completion of all contract work (Jervis and Levin 1988; Sweet 1991). Deciding about the warranty period comprises a tradeoff between a potential increase in the contract price and the cost of failure of an unwarranted coating system. Theoretically, contractors will tend to increase the contract price to cover the contingencies associated with a failing coating system for a variety of reasons, including adversarial environmental conditions. Cost increases with warranty provisions are not universal, though (Russell et al. 1999). A study by Michigan DOT of its bridge painting projects has not found a correlation between higher costs and warranty projects (MDOT 1996).

Most examined warranties establish a fixed warranty period of two years (Chang and Georgy 1999; Russell et al. 1999). One of the unique warranty period practices is set by Maryland DOT (Freeman 1997) where the contract documents require the contractor to provide a 5- to 10-year warranty. The process for bidding takes into account not only the offering of the bidders, but also the cost of each additional year of warranty beyond the minimum 5-year period.

Using a fixed warranty period has its own shortcomings, and its sufficiency is not always guaranteed. A variety of coating alternatives that offer a relatively long service life have recently become available. The use of a short fixed warranty period may be underestimating the expected performance of these systems. One coating system that possesses significant potential and is expected to gain nationwide use is a three coat

J. Constr. Eng. Manage., 2000, 126(5): 374-380

metallic paint that is composed of an organic/inorganic zinc primer, an epoxy intermediate coat, and a urethane topcoat (a.k.a. three-coat system) (Chang and Chung 1999). This system has an excellent performance in resisting water, ultraviolet (UV) light, alkalies, acidic pollutants, and abrasion (Hare 1990). The expected service lives of this system in 1B, 2A, and 2B environments (dry exterior, fresh water wet, and salt water wet) are 35, 13, and 10 years respectively. This estimate is based on a 5.0, 3.0, and 4.0 mils dry film thickness for the primer, intermediate coat, and topcoat, respectively (Hare 1990).

Knowing the expected service life of the coating system under different environmental conditions, how can a warranty period be estimated? Identifying a warranty period depends on the profile of the deterioration curve of the selected coating system, which in turn differs according to the prevailing environmental and service conditions on site. Fig. 1 illustrates a theoretical deterioration curve for a coating system and the corresponding warranty period. However, the deterioration curves of many coating systems that gained popularity following the banning of the high VOC coating systems are not readily available, especially as a function of the various classes of environmental and service conditions. Thus, a ratio approximation between the warranty period and the expected coating service life is needed for practical purposes.

An assumption can be made that the ‘‘theoretical’’ deterioration curves of both highway pavement and steel bridge coating are quite comparable. A number of studies have been conducted to investigate pavement deterioration curves (Livneh 1997). Pavement warranties usually run for a five-year period (INDOT 1996; Russell et al. 1999). Meanwhile, pavements are commonly designed for a service life of 15 to 20 years. The ratio between the warranty period and the expected pavement service life is roughly one third to one fourth. Therefore, a ratio of 25 to 35% can be temporarily used for estimating the coating system warranty period until more studies about the coating performance and the corresponding deterioration curves become available.

A main concern regarding the application of steel bridge coating warranties is the possibility that some contractors will refrain from bidding on the project. The required warranty period could be a prevailing factor for contractors in deciding whether to bid or not to bid. This is partly because the warranty programs are rather new, and some contractors are apprehensive about bidding on them. As Russell et al. (1999) reported, some DOTs experienced a change in the number and distribution of bidders because of the use of warranties.

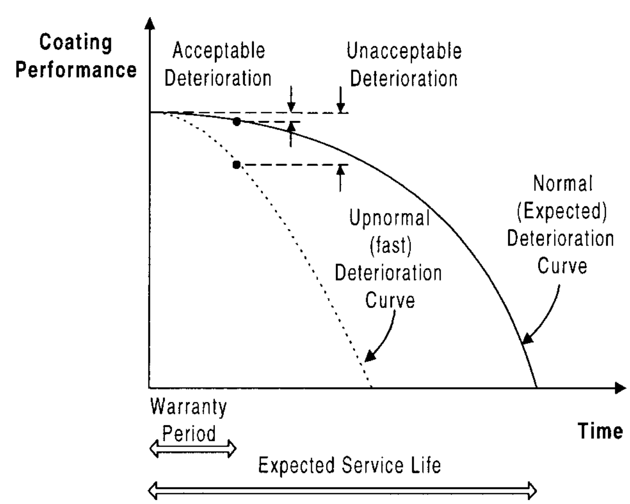

FIG. 1. Theoretical Deterioration Curve for Coating System and Corresponding Warranty Period

Using warranties for steel bridge coating primarily requires a transition phase to allow the contractors to better understand the functioning of warranties and how to adjust the contract price to varying warranty periods. A short fixed warranty period for a number of pilot projects suits such an environment. Besides allowing contractors to adapt to the warranty scheme, it would help the state DOTs evaluate their warranty practices within a reasonable time frame. Following this transition phase, the warranty period should correspond to the environment in which the bridge is located. However, the effects on the contract price of extending the warranty period are still unpredictable, especially for the longer periods.

Defects Identification

The core element of any warranty is to identify the defects that arise from the poor material or workmanship for which the contractor will be held responsible. Without a clear definition, conflicts may arise between the two parties. The examined warranties include coverage for major visible defects such as rusting, blistering, peeling, scaling, and so forth, in addition to the thinned and damaged coats. However, the defects are usually defined in a generalized form. Neither well-defined technical standards nor the limits beyond which the contractor will be held responsible are specified.

The American Society for Testing and Materials (ASTM) and the Steel Structures Painting Council (SSPC) developed several technical standards concerning the performance of bridge coatings, especially metallic paints. These technical standards provide a consistent procedure for identifying the coating defects, as explained hereafter.

When the bridge surface is subjected to severe rainfall, hail, and/or wind, the coating dry thickness may decrease and eventually become less than the value in specifications. The degree of erosion of the exterior paint can be evaluated using ASTM D662 standards. Without any apparent surface erosion, the overthinned or overthick dry film can be referred to the poor workmanship of the contractor. The readings of the dry film thickness are usually taken using magnetic gauges. To identify the status of the paint thickness, the SSPC-PA 2 specifications were developed (*Good* 1989b). The coating thickness is considered satisfactory if the average of five spot measurements made over 100 square feet of a certain area are within the specified thickness, while single spot measurements are permitted to be 80% of the specified thickness.

A certain category of paint defects arises from deficient surface preparation and is usually denoted by adhesion-related failures (*Good* 1989a). Those defects are mostly the contractor’s responsibility. The list includes blistering, peeling, scaling, and undercutting rust. In the case of no adhesion-related failure, the degree of adhesion of the coating to the substrate can still be evaluated using ASTM D3359 (Adhesion by tape test). If any of the various adhesion-related failures appears, the responsibility of the contractor is more evident. The standard specifications for adhesion-related failures, such as ASTM D714 for blistering, usually employ photographic references to evaluate the relative degree of deterioration of metallic paints.

Defects such as blistering, peeling, and scaling are easier to judge by the engineer/inspector since the effect of the poor workmanship far exceeds the effect of the environment in their development. This condition, however, does not apply to one of the most widespread forms of coating deterioration: surface rusting. Rusting was highlighted by the second interim report on the performance of Michigan DOT bridge coating warranties (MDOT 1996) as the major deterioration form noticed during the two-year warranty period. The danger of rusting emerges from its detrimental effect on the steel substrate, as it reduces the cross-sectional area of the rusted elements.

J. Constr. Eng. Manage., 2000, 126(5): 374-380

The difficulty in determining what stimulated the rust to occur is that both poor workmanship and severe environmental effects incorporate together in rust's development. Whenever no apparent cause of rusting beyond the contractor's control exists, poor workmanship rises as the primary cause. The improper mixing and application of the paint can easily cause water to penetrate the painting system to the steel substrate and start the rust. ASTM D610 standards cover the evaluation of the degree of rust on a painted surface. The percentage of the area rusted is determined by comparing the rusted surface with a set of photographic references provided by the standards. Eleven different ratings are identified in the evaluation procedure. The no-rust condition is graded as 10, and the 100% rusted surface is graded as 0. To reduce the amount of discrepancy in the condition assessment, Tam and Stiemer (1996) recommend the use of a set of photographs showing different corrosion ratings on actual bridge components with schematic representation of the ASTM D610 standards.

In developing their steel bridge painting cost model, Tam and Stiemer (1996) require no repair work in case of surface rust less than 0.3% of the examined area, which complies with the ASTM D610 standards. Conducting repair work for a less-than-0.3% rusted surface can be impractical. Also, the unreasonable interruption to the traffic and the possible damage resulting from the erection and removal of scaffolds may become more costly and time-consuming to the state DOT.

For the popular three-coat system (an inorganic zinc primer, an epoxy intermediate coat, and a urethane topcoat), the American Association of State Highway and Transportation Officials (AASHTO) M300-86 standards (AASHTO 1986) require a maximum of 1% rusting rate for inorganic zinc primers in a three-year period. The standards allow the 1% rusting in coastal and marine environments, which are the harshest of all possible environments. A lower rusting rate is expected in milder environments, such as the dry exterior and the fresh water wet environments.

As the three-coat system is becoming the plausible alternative for steel bridge coating, warranties should require a maximum of a 1% rusting rate whenever this system is in use. This still needs to be linked to an appropriate warranty period. However, the two-year warranty period, which is commonly adopted during the transition phase for warranty application, satisfies this condition. Further investigation of the deterioration curves for the coating systems in today's market would enhance our understanding of the appropriate combination of the warranty period with the allowed rusting rate.

CONDITION ASSESSMENT AND WARRANTY IMPLEMENTATION

The techniques currently used for bridge coating quality assessment, which depend mostly on visual inspection, are subjective, inconsistent, and time consuming (Shubinsky 1994). The ASTM standards developed for rating the coating condition with regard to the various coating failures require human experts to detect small differences in steel surface conditions. Inconsistencies arise because different engineers/inspectors may provide different ratings for the same area. As visual inspection remains the prominent approach for identifying surface defects in warranty practices, a major challenge faces most DOTs to enhance the coating quality assessment process. Hence, potential conflicts between the DOT and the bridge-coating contractors regarding the coating condition could be avoided.

A hybrid model for nondestructive quality assessment of steel bridge coatings has been developed by the writers (AbdelRazig 1999; Chang et al. 2000). The model provides objective and quantitative analysis to improve the quality assessment process of steel bridge coatings. This hybrid model utilizes image processing and neural networks as tools for visual data analysis, recognition, and classification. The basic concept is to acquire digital images of the areas to be assessed and analyze these images to recognize and measure the defect patterns. Neural networks are incorporated into the model to learn from example and to simulate human expertise in order to automate the process for future use. For implementation purposes, the system was customized for recognition of rust defects as they constitute the major known form of coating deterioration. This system has two major stages: image acquisition and preprocessing stage, and image analysis and recognition stage.

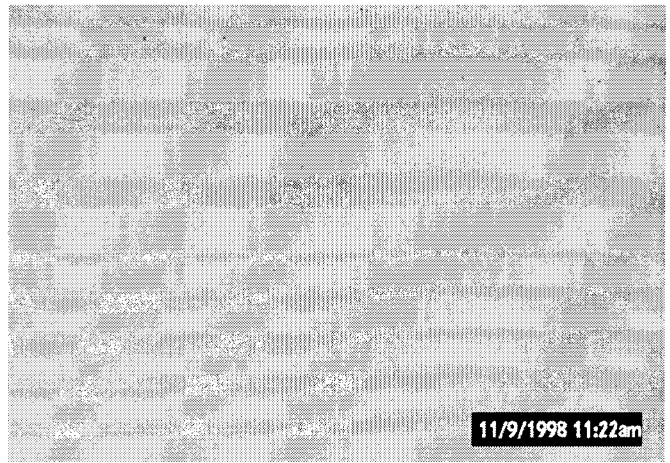

FIG. 2. Sample Digital Image of Defective Steel Bridge Coating

Image Acquisition and Preprocessing Stage

The image acquisition and preprocessing stage is a relatively simple process. Images of selected areas of the bridge surface are taken using a digital camera. Fig. 2 illustrates a sample image of a steel bridge coating area. The number and location of the images taken follow a statistical sampling plan (Chang and Hsie 1995; AbdelRazig 1999). The statistical plan determines the sampling method, number, and location of images and the risks associated with acceptance or rejection of the sample images. Following the acquisition of the digital images, various preprocessing techniques are used to enhance image quality, including noise reduction and contrast/brightness adjustments. Afterwards, color images are converted to gray scale to eliminate the differences in coating color during recognition and analysis phases.

Image Analysis and Recognition Stage

This stage deals mainly with image recognition and classification. The model assigns a classification to an object based on the parameters provided by its descriptors. As neural networks represent a powerful and reasonable alternative to conventional classifiers (Garris et al. 1998; Lang et al. 1998), they are used to recognize the defective versus nondefective spots within an image. After being trained, neural networks identify defects (rust areas) by assigning binary variables of ''0'' or ''1'' for each pixel in the image. A value of ''1'' is assigned for the defects (objects) and ''0'' for the nondefects (background). The whole-image pixels are represented as 0s or 1s. The ''1'' values represent defects; hence, defects can be identified and quantitatively measured as a percentage of the whole area.

For training the neural networks, pairs of gray-scale level and thresholded images were used. Fig. 3 illustrates the thresholded image corresponding to the image in Fig. 2. Thresh-

J. Constr. Eng. Manage., 2000, 126(5): 374-380

olding is the operation of separating the image into different regions based upon the gray level distribution. Separation of the defect (object) pixels from the nondefect (background) pixels is accomplished by selecting a gray level value T such that all pixels within the image with a gray level greater than T will be classified as belonging to the object, and values below T are classified as background (Russ 1995; Weeks 1996). Details of the thresholding algorithms can be found in other publications by the writers (AbdelRazig 1999; Chang et al. 2000). Fig. 4 illustrates the process of neural network training using pairs of gray-scale images and their corresponding thresholded images.

Application (Bridge on Highway US-41)

A highway steel bridge located on Highway US-41 near I-74 in Indiana was used as an example for the hybrid model. The described model was used to assess the quality of the steel bridge coating. A total of 36 images were acquired, one image per beam. The exact image's location on the beam was selected randomly. The defect (rust) percentage was calculated for each image. The results from all the images of a bridge are compiled for the assessment decision.

Table 1 illustrates the assessment summary for the bridge on Highway US-41. Every image was labeled as to whether it represented a main beam or a secondary beam, with the corresponding beam code. The rust percentage area in each image was calculated, and every sample was considered defective if the image rust percentage area exceeded 1%, and nondefective otherwise. The ''1%'' threshold to consider coating as defective is an assessment decision and can vary to accommodate the DOT's preferences. For example, from Table 1, image number ''2'' was processed by the model, and the rust per-

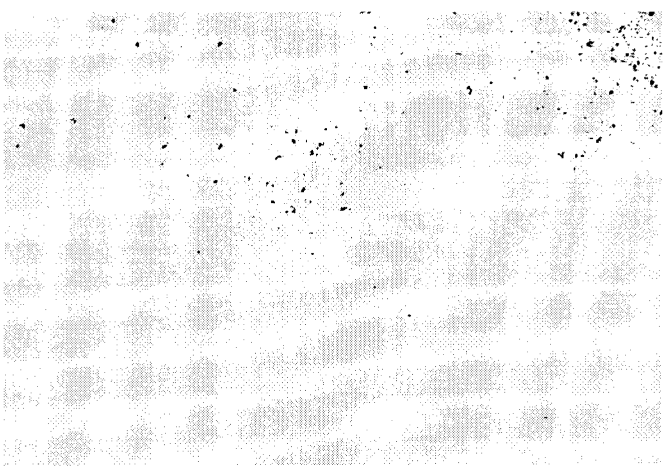

FIG. 3. Threshold Image of Defective Steel Bridge Coating

TABLE 1. Bridge Assessment Summary (Bridge on Highway US-41)

Number (1)	Beam code (2)	Main beam (3)	Rust (%) (4)	Assessment (5)
1	NS1	X	0	Nondefective
2	NS2	X	0.23	Nondefective
3	NS3	X	0.9	Nondefective
4	NS4	X	0	Nondefective
5	NS5	X	0	Nondefective
6	NS6	X	0	Nondefective
7	NS7	X	4.7	Defective
8	NS8	X	0.81	Nondefective
9	NS9	X	0	Nondefective
10	NS10	X	11.4	Defective
11	NS11	X	0	Nondefective
12	NS12	X	0	Nondefective
13	NS13	X	0	Nondefective
14	NS14	X	0	Nondefective
15	NS15	X	0	Nondefective
16	NS16	X	0.62	Nondefective
17	NS17	X	0	Nondefective
18	NS18	X	0	Nondefective
19	NS19	X	0	Nondefective
20	NS20	X	0	Nondefective
21	WE1		0	Nondefective
22	WE2		5.11	Defective
23	WE3		0	Nondefective
24	WE4		0	Nondefective
25	WE5		6.34	Defective
26	WE6		0	Nondefective
27	WE7		0.56	Nondefective
28	WE8		0	Nondefective
29	WE9		0	Nondefective
30	WE10		0.85	Nondefective
31	WE11		0	Nondefective
32	WE12		0	Nondefective
33	WE13		0	Nondefective
34	WE14		7.5	Defective
35	WE15		0	Nondefective
36	WE16		0	Nondefective

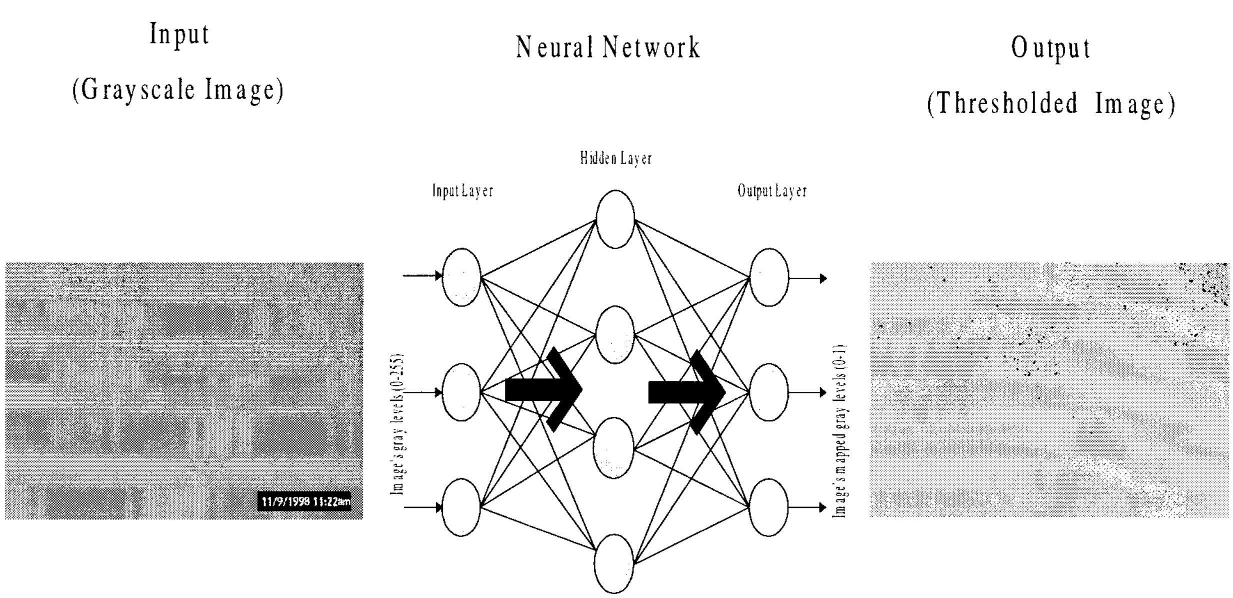

FIG. 4. Neural Network Training with Pair of Gray-Scale and Thresholded Images

J. Constr. Eng. Manage., 2000, 126(5): 374-380

centage was calculated as ''0.23%'' and thus considered nondefective. Furthermore, image number ''22'' had ''5.11%'' rust area and hence was considered defective.

The statistical acceptance plan was applied to decide whether to accept or reject the steel bridge coating job (Chang and Hsie 1995; AbdelRazig 1999). For this example, the lot size or total population N, which represents the total number of images, was 36; producer's risk α = 5%; owner's risk β = 5%; and sample size n_1 = 10. Randomly selecting 10 images from the total population of 36 images resulted in two defective units d_1. Based on the double sampling plan, having two defective units will not indicate acceptance or rejection of the lot (bridge coating) and will require taking another sample. Another sample of size n_2 = 10 images was taken, and the number of defective units d_2 was found to be two. The total number of defective units in both samples ($d_1 + d_2$) = 4, and hence the lot or the bridge was accepted. Fig. 4 illustrates the final assessment summary.

Had we found one defective image, the bridge coating would have been accepted without taking a second sample. Also, if we found three or more defective images, the bridge coating would have been rejected without the need for a second sample.

In summary, this hybrid model makes the coating assessment procedure more objective and consistent. Using computer image processing and neural networks enables the system to recognize and measure defects on a quantitative and consistent basis, which is an extremely difficult task to achieve when depending only on human visual assessment.

SUMMARY AND CONCLUSIONS

The various state DOTs are faced with the continual challenge of better preserving their bridge infrastructure systems. The decline in bridge coating workmanship, along with the finite annual budgets for the statewide maintenance activity, calls for further examination of using contract warranties. The introduction of warranties allows the DOTs to hold contractors responsible for the quality of materials and workmanship used in the project.

The authors conducted a thorough study for the establishment and implementation of contract warranties in bridge coating practices. The major two categories highlighted as paramount in establishing a successful warranty form are the warranty period and the defects for which the contractor is held responsible. Although a two-year warranty period is commonly adopted by DOTs, future practice requires the warranty period to be linked to the expected service life of the coating system, in addition to the prevailing environmental and service conditions on site.

A number of ASTM and SSPC standards provide a systematic procedure for identifying the bridge coating defects that may arise during the warranty period, including, rusting, blistering, cracking, and so forth. The various standards require human experts to refer to photographic references in order to evaluate the relative degree of coating deterioration. As visually quantifying the degree of deterioration can be very difficult, even for a well-trained expert, the evaluation credibility would become questionable. Potential conflicts can arise between state DOTs and bridge-coating contractors regarding the accuracy of the evaluation.

A hybrid model for the nondestructive quality assessment of steel bridge coatings has been developed to enhance the warranty implementation practices. It utilizes image processing and neural networks as tools for visual data analysis, recognition, and classification; hence, it provides a reliable and unbiased approach for condition assessment. It relies on acquiring digital images of the defective coating areas and analyzing these images in order to recognize and measure the defect patterns. Neural networks are incorporated into the model to simulate the human expertise and automate the process for future use. Moreover, they provide better handling of low-quality images through their fault-tolerant characteristics.

ACKNOWLEDGMENTS

The authors would like to thank the Indiana Department of Transportation (INDOT) and the Joint Transportation Research Program at Purdue University for giving them the opportunity to conduct this research. Also, several members of INDOT are to be acknowledged for their efforts in providing data and facilitating site visits that were essential for pursuing the research activity.

APPENDIX. REFERENCES

AbdelRazig, Y. (1999). ''Construction quality assessment: A hybrid decision support model using image processing and neural learning for intelligent defects recognition.'' PhD dissertation, School of Civ. Engrg., Purdue University, West Lafayette, Ind.

Aktan, A. E., et al. (1996). ''Condition assessment for bridge management.'' *J. Infrastructure Sys*., ASCE, 2(3), 108–117.

American Association of State Highway and Transportation Officials (AASHTO). (1986). *Standard specifications for transportation materials and methods of sampling and testing: Part I—Specifications*, Washington, D.C.

Chang, L. M., AbdelRazig, Y., and Chen, P. (2000). ''Optical imaging method for bridge painting maintenance and inspection.'' *FHWA/IN/JTRP-99/11*, Joint Transp. Res. Program, Purdue University, West Lafayette, Ind.

Chang, L. M., and Chung, S. (1999).''Steel bridge protection policy: Volume II of V—Evaluation of bridge coating systems for INDOT steel bridges.'' *FHWA/IN/JTRP-98/12*, Joint Transp. Res. Program, Purdue University, West Lafayette, Ind.

Chang, L. M., and Georgy, M. (1999). ''Steel bridge protection policy: Volume V of V—Proposed warranty clause for INDOT steel bridge painting contracts.'' *FHWA/IN/JTRP-98/21*, Joint Transp. Res. Program, Purdue University, West Lafayette, Ind.

Chang, L. M., and Hsie, M. (1995). ''Developing acceptance sampling methods for quality construction.'' *J. Constr. Engrg. and Mgmt*., ASCE, 121(2), 246–253.

Dunker, K. F., and Rabbat, B. G. (1995). ''Assessing infrastructure deficiencies: The case of highway bridges.'' *J. Infrastruct. Sys*., ASCE, 1(2), 100–119.

Federal Highway Administration (FHWA). (1997). ''FHWA study tour for bridge maintenance coatings.'' *FHWA-PL-96-031*, Washington, D.C.

Freedman, E. (1997). ''Maryland switches to warranty bidding.'' *Better roads*, 67(11), 11.

FY2000—Budget in brief. (1999). U.S. Department of Transportation, Washington, D.C.

Garris, M., Wilson, C., and Blue, J. (1998). ''Neural network-based systems for handprint OCR applications.'' *IEEE Transactions of Image Processing*, 7(8), 1097–1112.

Good painting practice: Steel structures painting manual—Volume I. (1989a). Steel Structures Painting Council, Pittsburgh, Pa.

Good painting practice: Steel structures painting manual—Volume II. (1989b). Steel Structures Painting Council, Pittsburgh, Pa.

Hancher, D. (1994). ''Use of warranties in road construction: A synthesis of highway practice.'' *NCHRP synthesis 195*, Nat. Cooperative Hwy. Res. Program, Transportation Research Board, Washington, D.C.

Hare, C. H. (1990). *Painting of steel bridges and other structures*, Van Nostrand Reinhold, New York.

Indiana Department of Transportation (INDOT). (1996). *Asphalt pavement warranted*, Indianapolis.

Jervis, B. M., and Levin, P. (1988). *Construction law: Principles and practice*, McGraw-Hill, New York.

Lang, J., Voight, H., Burkhardt, S., and Goebel, R. (1998). ''Intelligent inspection engine—A real-time real-world visual classifier system.'' *Proc., IEEE World Congr. on Computational Intelligence, IEEE Int. Conf. on Neural Networks*, IEEE, Piscataway, N.J., 1810–1815.

Livneh, M. (1997). ''Further developments in the formulation of the deterioration curves of overlaid pavements.'' *Proc., Specialty Conf. on Infrastructure Condition Assessment: Art, Sci., Pract*., ASCE, New York, 141–150.

Michigan Department of Transportation (MDOT). (1996). ''Performance warranty for bridge painting research project 90 TI-1515.'' *Second Interim Rep., Res. Proj. 90 TI-1515*, Lansing, Mich.

Russ, J. C. (1995). *The image processing handbook*, CRC, Boca Raton, Fla.

J. Constr. Eng. Manage., 2000, 126(5): 374-380

Russell, J. S., Hanna, A. S., Anderson, S. D., Wiseley, P. W., and Smith, R. J. (1999). ''The warranty alternative.'' *Civ. Engrg.*, ASCE, 69(5), 60–63.
Shubinsky, G. (1994). ''Application of optical imaging method for bridge maintenance and inspection.'' *ITI Tech. Rep. No. 4*, Northwestern University, Evanston, Ill.
Sweet, J. (1991). *Legal aspects of architecture engineering and the construction process*, 4th Ed., Wiley, New York.
Tam, C. K., and Stiemer, S. F. (1996). ''Development of bridge corrosion cost model for coating maintenance.'' *J. Perf. Constr. Fac.*, ASCE, 10(2), 47–56.
''U.S. Highway Department studies European bridge painting practices.'' (1998). *J. Protective Coatings and Linings*, 15(1), 17–21.
Weeks, A. (1996). *Fundamentals of electronic image processing*, SPIE, Bellingham, Wash., and IEEE Press, Piscataway, N.J.

J. Constr. Eng. Manage., 2000, 126(5): 374-380