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Quality Assurance of Structural Materials

This digest summarizes information from a study conducted for NCHRP Project 20-5, "Synthesis of Information Related to Highway Problems." The study was begun by Robert L. Nickerson, P.E., Hampstead, Maryland, and later work was done by Scott A. Sabol of the Vermont Technical University. Jon Williams is the manager of NCHRP Synthesis Studies.

INTRODUCTION

This study examines the state of the practice of quality assurance (QA) related to critical structural materials and components: those for which failure poses a threat to public safety or to the integrity of the transportation system (e.g., bridge girders, bridge columns, and sign/signal/luminaire supports). The study focuses on conventional structural materials (e.g., steel, concrete, wood, and aluminum), which comprise the vast majority of highway structures in use or in the planning and design stages. Brief coverage of some newer materials in the highway infrastructure, such as fiber-reinforced polymers (FRPs), high-performance concrete, and high-performance steel, is provided.

The intent of the report is to discuss problems (both perceived and real) that arise from insufficient or potentially inappropriate QA practices, indicate potential opportunities for improvement to practices through additional or revised practices, and discuss the state of the practice with respect to how most agencies currently are operating.

There have been numerous QA studies over the years, many of them sponsored by AASHTO, primarily through the NCHRP. A review of these documents indicates that although they may adequately address construction materials used in pavements, the information that they contain is not necessarily useful for highway structural applications such as bridges. This proves true even when the same materials (e.g., portland cement concrete) are involved in both pavements and other applications. In addition, individual materials are addressed frequently, but special issues arising from the use of materials in combination (e.g., portland cement concrete with steel reinforcing) are not addressed as a formalized QA practice. Finally, comprehensive information on the successful implementation of QA for structural components in the design phase of the project is not available.

For this report, information was acquired through the literature and with a survey of practice that addressed a wide range of issues, including the activities and elements of quality programs (i.e., what comprises QA for structural components?), codes and specifications and their effect on quality, contractual mechanisms that may help to ensure quality (e.g., incentives and disincentives), and other aspects of QA programs (e.g., inspector training). There are already strong elements of QA in use by state departments of transportation (DOTs) and industry, although no state has a system that covers every project step for every type of structural application. Some states have QA documents that may be of use to other states as a model. Florida's *Manual for Quality Assurance of Precast Prestressed Concrete Members* is one such document.

The study suggests that the concept of quality is gaining in importance, but that there are gaps in understanding and practice. Most states use a common definition for the term "quality" (a definition put forth by AASHTO), which indicates that they

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are looking toward the same goal with regard to QA practices. Another commonality among states is that most QA activity is focused during the construction phase. In addition, many QA practices for pavements are applied to critical structural elements to the extent feasible. In both cases (structural and other applications), the focus is more on the quality of individual materials and less on the overall constructed product. Some state documents contain explicit information related to the quality of structural components, such as the QA chapter of the Texas DOT's *Manual of Structural Steel Inspection*.

The transition in bridge design to the AASHTO *LRFD Bridge Design Specifications*, with its specified minimum design life of 75 years, brings extra attention to QA as well. It sets a target for which good QA may help a state DOT to better understand quality benchmarks and the costs and savings of quality design and construction.

Many states have experience with or are experimenting with nontraditional contracting techniques or elements, such as design/build or warranties. There is not now enough conclusive evidence to establish a relationship between the delivery mechanism and component quality. However, there are indications that some of these newer approaches help improve quality. A few of the recently constructed FRP bridges in the United States have had warranties associated with them, presumably to provide owner agencies with a comfort level for this material, to a degree that is relatively unknown in the highway community. However, it is clear that improved QA can and should be achieved for all project delivery systems, including the traditional design/bid/build system.

Although the research for this report unveiled a collection of popular and effective practices, it is clear that a single, easy-to-implement solution does not exist. Accordingly, one of the major needs in the highway community is for a guidance document that provides comprehensive, cradle-to-grave QA information that can be implemented for all or most highway structures made from all or most of the new and traditional structural materials. A framework for such guidance is described in the report; however, development of such a guidance document is beyond the scope of the current effort.

Other QA findings and recommendations revolve around issues such as communication (e.g., encouraging continued communication between AASHTO groups such as the Highway Subcommittee on Bridges and Structures and the Standing Committee on Quality, and reducing errors through the sharing of computer-aided design and drafting files); improvement of, and better understanding of, industry certification practices and their effect on quality; and the need for better information on how to best implement project delivery mechanisms such as design/build. These are discussed in the report.

Finally, it should be noted that this report focuses primarily on how to ensure that the desired level of quality is attained. It does not address what that level of quality should be.

QUALITY ASSURANCE BY PROJECT PHASE

Highway projects involving construction of structures are classified by various phases, which frequently follow this chronology:

- Planning,
- Design,
- Construction, and
- Operation/maintenance.

For this report, the last three phases are considered. QA issues are integral to each, and the quality of the outcome or result of each phase (e.g., the quality of plans, specifications, and estimates that result from the design phase) will have an effect on the overall quality of the final product.

Terminology

- To set the context for the term "quality assurance" as used for this report, the AASHTO definition (*1*) is provided:

  Quality Assurance (QA): All those planned and systematic actions necessary to provide adequate confidence that a product or service will satisfy given requirements for quality. Within an organization, QA serves as a management tool. In contractual situations, QA serves to provide confidence in the supplier.

  The AASHTO definition of QA can be applied to design, construction, and/or maintenance, and could be extended to areas such as planning and finance. This report focuses on the first three items.

- A QA program includes quality control (QC) by the contractor/fabricator and testing by the contractor and the owner. Owner testing can be in two parts; independent assurance (IA) and/or verification sampling and testing (VS&T). These terms have been defined by AASHTO and the FHWA as follows:

  Quality Control (QC): The sum total of activities performed by the [supplier] seller (producer, manufacturer, and/or contractor) to make sure that a product meets contract specification requirements. Within the context of highway construction this includes material handling and construction procedures, calibration and maintenance of equipment, production process control, and any sampling, testing, and inspection that is done for these purposes (*1*).

  Independent Assurance (IA): IA is an unbiased and independent verification of the Quality Assurance system used and of the reliability of the test results obtained in the regular sampling and testing activities. The results of IA tests are not to be used as a basis of material acceptance (*1*).

An integral part of QA is VS&T. As defined in 23CFR637.203 and 23CFR637.205 (*2*), this includes sampling and testing performed to validate the quality of the product on a specific project. The VS&T is to be performed by qualified testing personnel employed by the state DOT or its designated agent, excluding the contractor and vendor.

More information on this is provided in an appendix to *NCHRP Synthesis of Highway Practice 263* (*3*). Technically, VS&T and IA are independent functions. However, for this report, IA and VS&T will be used interchangeably, unless a state indicates it performs both functions.

Other groups have also defined or commented on quality. The American Society of Civil Engineers (ASCE) manual, *Quality in the Constructed Project* (*4*), defines quality in a constructed project as "meeting the requirements of the owner, design professional, and constructor as specified by contract, while complying with laws, codes, standards, regulatory rules, and other matters of public policy."

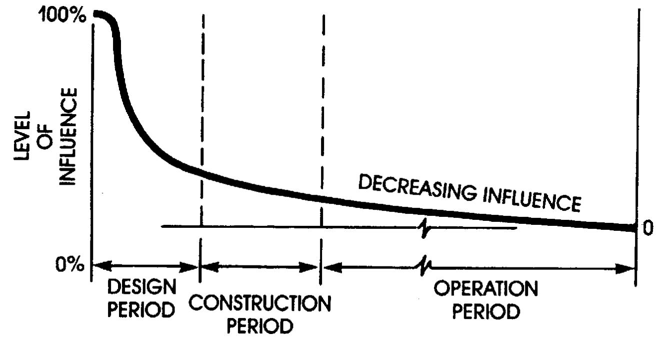

Figure 1. Project influences by project phase (4).

Design Phase

Design details on the plans have a significant effect on construction costs and often dictate the life-cycle performance of a structure, including the level of maintenance that will be required over its service life. Figure 1, derived from the ASCE quality manual (*4*), provides an illustration of the relative influence on project characteristics defined as cost and quality as a project moves through its service life.

With the design phase accounting for 80% to 90% of the impact on quality and cost, its impact must be considered for much of the performance of the finished project. The ASCE manual states, "The design professional's responsibilities and functions are central to achieving quality in construction" (*4*).

For an owner to have a successful QA program, the designer and contractor have to be involved, and the quality needs of each must be satisfied in addition to those of the owner. In highway construction, the designer is not always considered an active "partner" in the process of assuring quality at the construction stage and during the structure's service life. In reviewing FHWA regulations, AASHTO documents (*1,5*), and the QA manuals submitted by the states, the designer's role is rarely mentioned, the assumption being that if the AASHTO design specifications are followed, adequate quality will follow. As with the American Welding Society's (AWS) D1.5 *Bridge Welding Code*, many states include supplemental requirements and standards to the design specifications without documented improvements in safety, durability, or cost savings.

Standard practice is to focus on the construction phase of project development when discussing QA by implementing a construction phase QC program on the part of the contractor. FHWA regulation CFR 637, Subpart B, *Quality Assurance Procedures for Construction,* states it is ". . . to assure the quality of *materials and construction* (emphasis added) in all Federal-aid highway projects on the National Highway System" (*2*). Thus, actions taken during the design phase of project development, which have the greatest impact on the ultimate quality of the finished product, and a formal design QC/QA program, whether design is in-house or by contract, is ignored.

The FHWA issued Regulation 23CFR625, *Design Standards for Highways*, "to designate those standards, policies, and standard specifications that are acceptable to the Federal Highway Administration (FHWA) for application in the geometric and structural design of highways" (*6*). This regulation lists minimum requirements for plans and specifications to be used for National Highway System (NHS) projects. Included in this list is the AASHTO *LRFD Bridge Design Specifications* (*7*). However, none of the documents listed refer to the QC/QA of the design process. As stated in the Section 625.2 Policy, "An important goal of the FHWA is to provide the highest practical and feasible level of safety for people and property associated with the Nation's highway transportation systems and to reduce highway hazards and the resulting number and severity of accidents on all the Nation's highways." Such a statement suggests that a formal design QC/QA program is desirable.

The impact of design on structure performance can be illustrated by looking at one of the earliest design phase decisions made, that being to include bridge joints in the structure. There are approximately 581,000 bridges in the United States, with an annual estimated maintenance cost of almost $6 billion. More than 100,000 bridges are noted as "structurally deficient" (*8*). A significant percentage of the structural deficiencies are noted as substructure deterioration, which is most often caused by the effect of leaking bridge joints—joints that one surmises met the original design and construction specification requirements. In some states, bridges less than 400 ft long (or sometimes longer) are not required to have bridge joints at piers or abutments and can be constructed as "jointless." More than 80% of the nation's bridges are less than 200 ft long (*9*). However, many states will not consider the construction of jointless bridges and blame premature deterioration of bridge substructure on poor construction or lack of maintenance. If QA is to be a concern through all phases of the project, then selection of design type is one area for which QA should be integrated.

The load and resistance factor design (LRFD) code (*7*) states, "The number of movable deck joints in a structure should be minimized. Preference shall be given to continuous deck systems and superstructures and, where appropriate, integral bridges." It will be interesting to see if current practices change as a result of this emphasis on jointless construction and if there are perceived improvements in quality.

QA at the design phase has a long reaching effect on the quality of the finished structure. It can be measured far beyond the construction phase when QA is assumed to mean compliance with a given material specification (as required by 23CFR637, Subpart B). This observation points out the need for a QC program on the part of the designer to ensure that maintainability and durability are properly considered for all designs.

NCHRP Report 422 notes that the concept of quality contains the following attributes (*10*):

- Conformance to requirements,
- Absence of defects,
- Fitness for use, and
- Meeting the customers' needs and expectations.

These points might seem obvious to the highway industry as it moves into the 21st century and looks back at the tremendous achievements best exemplified by the Interstate system of highways; however, closer scrutiny will show that, as always, there is room for improvement.

This issue is not unique to structure design. *NCHRP Synthesis of Highway Practice 263* (*3*) states that

> Management of the total acceptance process will include quality-based qualification for designers, testing and inspection consultants, and contractors. No longer should services be provided by firms unable to meet acceptable quality levels. Many DOTs require specific qualifications for consultant employees providing inspection and testing services; however, the qualification requirements for design deliverables are not well detailed nor are design firm quality control plans.

The report questionnaire inquired about the level of responsibility that designers, both in-house and consultants, have in the life-cycle performance of the structure. Two-thirds of the respondents indicated that their QA programs include design for in-house and consultants. (One state, Montana, indicated QA applies only to in-house designs.) Only one-third indicated that they require consultants to have a QC program. States were asked if the designer's QC process was audited; less than one-third of the respondents indicated that they did. However, it was found that of those that audit designer QC programs, one-half do not require a QC program. Thus, the definition of an audit is questionable for those respondents. States were asked if conformance to good practices is monitored without a formal QA program. The predominant response was that there were periodic reviews of the design plans during development and, accordingly, it is assumed this is considered an audit by many.

Washington State mentioned that they ensure good practices by having their construction, inspection, and maintenance personnel do a detailed review of all designs prior to bidding. This process provides for the incorporation of good details and it should be considered by other states. Many useful questions can be answered; for example, who is checking to see if qualified/experienced designers are being used on the project? This is especially important as we move to more computer-generated designs with automatic incorporation of standard details, whether the project is standard or not.

Louisiana indicated that they do not audit the designer's "required" QC process. They did provide a copy of their "Consultant Checklist/Guideline," which the consultant and subconsultants, if any, are required to sign before initiating the design. This ensures that the consultant has all necessary documents for completing the design to the state's standards, but does not specifically address items such as inspectability reviews. A specific requirement of their checklist is the statement "The Prime Consultant is responsible for all corrections to the plans and specifications required because of errors and omissions. The fact that there may have been previous reviews/checks by the Department does not relieve the Consultant of this responsibility." This does remind the consultant of the need for a QC program of their own with or without the department's mandate, and where state review resources are diminished, this form of requirement would seem to to ensure that design consultants at least begin the task with a full understanding of their responsibilities. This checklist could be used as a model to begin development of a consultant QC program.

A vast majority of the respondents indicated that they require consultants to have professional liability (errors and omissions) insurance. Only Wyoming indicated they do not hold consultants responsible for errors and omissions.

South Carolina indicated that they require consultants to certify their plans, and that this is required in addition to the normal professional engineer's stamp on all drawings. They also reported that the consultant is fully responsible for correcting all errors and omissions, as well as certifying ". . . that all plans and specifications will be checked in their entirety for completeness, correctness, accuracy, and consistency . . ." In addition, ". . . all the work . . . will be performed so as to meet or exceed reasonable standard of care of the profession." This could be interpreted to mean compliance with the LRFD requirements when this becomes the "standard" of the bridge design profession. They also specifically state that the consultant is fully responsible for correcting all errors and omissions.

The report questionnaire asked whether designers are responsible for constructibility, inspectability, and/or maintainability, using the LRFD definitions as the measurement, and without differentiating between in-house and consultant designs. More than 85% indicated that the designer is responsible for constructibility, but only about 60% placed responsibility for inspectability and maintainability on the designer.

States responded that constructibility, inspectability, and/or maintainability are covered, but in different ways. South Dakota indicated that the state bridge construction engineer is a part of the bridge staff, assuring constructibility during plan review. This would also be true if the bridge design, inspection, and maintenance programs were centralized under one office/engineer. In some states, bridge inspection and maintenance is under the jurisdiction of the bridge office, facilitating communication between designers and inspection/maintenance personnel. Nevada specifically noted that they "require consultants to review constructibility."

It would seem prudent to require as a part of the design QC program a certification that basic issues have been considered and are a part of the final design documents for all designs (consultant and in-house). These issues could be safety, cost, aesthetics, constructibility, maintainability, and inspectability as is included in the LRFD specifications. Because of the design's effect on quality, such a design certification could possibly be as meaningful as a cement or steel material certification. Utah indicated that a "design QA process currently [is] being defined."

When design/construction conflicts arise, most states indicated that they use arbitration, mediation, and/or negotiation. Few indicated they hold the consultant responsible for any extra costs associated with design errors. Six states reported that they use partnering to prevent these disputes from occurring. Michigan has a dispute resolution process developed in conjunction with the American Consulting Engineers Council.

Pinnell (*11*) indicated that a "dispute management program" is necessary to minimize unnecessary disputes and that the use of partnering is becoming increasingly more common and successful in resolving disputes, whether consultants are involved or not. He indicates that

> Most construction problems, disputes, and claims are a result of poor project management. Project owners may fail to plan adequately, define the project scope, or provide an adequate budget. Designers may fail to negotiate an adequate fee, plan their work, or control their costs and schedules. This can result in design errors, poor drawing coordination, or insufficient time and money for completing the contract documents.

In the public sector, it is feared that negotiation of design fees is increasingly becoming a low bid exercise (after a list of "qualified" consultants is obtained), which may prevent the studying of alternatives or adequate checking of plans, especially if the fee is unreasonably low or the scope is not adequately defined. A design phase QA program would address these issues and could reduce design error/omission disputes.

When asked if they were satisfied with their QA process for design and construction, most states answered yes. Seven states commented on the need for better-qualified construction inspectors. Kansas wants to see more performance-based specifications. Illinois noted the need for ". . . more QA programs that formally address design and construction QA." Texas addressed the design and construction phase as follows: "Design: Provide more training and hire more people. Pay better salaries to attract the best people. Construction: More inspectors are needed. Materials: 1) Use statistics to improve sampling; 2) We are developing our QC/QA spec for P/S [prestressed] concrete now. Once it is complete, we will be closer to yes." Although their suggestions may provide better QA, they may be unrealistic for most states in today's employment environment.

Construction Phase

When asked, "If you do not have a formal QA program for construction, how do you monitor conformance with plans and specifications for structural components?" all 16 states responding indicated that they do so by construction phase inspection and testing. Many states have a formal QA program for small portions of the process, but the information received indicates that no one state covers all structural materials, critical or not.

Historically, the emphasis for QA of highway projects has been during the construction stage. The FHWA has had design-related requirements for federal-aid projects since the introduction of the federal-aid program. These requirements have been modified over time and are now contained in Regulation 23CFR637, Subpart B, *Quality Assurance Procedures for Construction*, and apply only to projects on the NHS. Section 637.205 states, in part, "Each SHA [state highway agency] shall develop a QA program which will assure that the materials and workmanship incorporated into each Federal-aid highway construction project on the NHS are in conformity with the requirements of the approved plans and specifications, including approved changes." A QA program should include the following key elements:

- A frequency guide for VS&T, with general guidance that can be adapted to specific project conditions and needs;
- Specific locations within the project where VS&T is to be accomplished; and
- Identification of specific attributes to be inspected that reflect the quality of the finished product.

The QA program can use QC testing as a part of the acceptance decision if the following criteria are met:

- Sampling and testing has been performed by qualified laboratories and personnel,
- The quality of the material has been validated by VS&T on samples other than the QC samples, and
- QC sampling and testing is validated by an IA program.

The IA program shall include a schedule of frequency for IA evaluation and shall evaluate the sampling and testing personnel and the testing equipment.

NHS bridges represent only 22% of the total bridges in the United States and only 18% of the deficient bridges on the nation's highways (*9*). Although many, if not all, states use the FHWA requirements as minimums for all projects, it is worth considering whether these requirements should be considered as minimums for all bridges, given the large numbers that are not on the national highway system and thus are more removed from direct FHWA oversight. Many of the QA manuals received as part of this report effort are patterned after the requirements of 23CFR637.

The California DOT (Caltrans) has developed QC/QA specifications for use on asphaltic concrete pavement contracts (*12*). The new QC/QA specifications require the contractor to do the following:

- Develop, implement, and maintain a QC plan;
- Assign a QC manager to manage the QC plan;
- Provide plant and roadway inspection for QC;
- Provide sampling and testing for QC;
- Provide daily reports on inspection and testing;
- Have a paving inspector (QC) on site at all times; and
- Have sampling/testing personnel with a Caltrans "Certification of Proficiency."

These procedures provide a good model from which a formal QC/QA plan for each type of structural material/component could be established.

A question that needs to be addressed carefully and thoroughly for critical structural materials/components is whether less than 100% compliance is acceptable. Typically, structural concrete is accepted using essentially the same statistical specifications that are used for roadway pavements. For example, it is not specifically known whether less than 100% of the minimum required strength acceptable for any portion of a long-span segmental concrete girder should result in the component being deemed unacceptable. The same goes for not achieving 100% of the minimum required strength for tension butt welds in welded steel girders or for anchor bolts of cantilevered sign structures.

The FHWA has developed a Technical Advisory, T 5080.12, "Specification Conformity Analysis," dated June 23, 1989, "To provide guidance on the technical basis for, and use of, Specification Conformity Analysis (SCA) procedures (formerly called Quality Level Analysis)." Structural components could also be assessed using Specification Conformity Analysis, but new parameters for acceptance may need to be developed to do so. Without better knowledge of the effect of local deviations from minimums, current practice is to design conservatively.

Current practices for acceptance vary from state to state and generally make no difference in the ultimate safety of structures. Therefore, the least costly of these practices should be identified and developed as a part of "model" QC/QA criteria for structural materials. Structural materials that less directly affect safety (e.g., paint) probably can and should be accepted based on statistical parameters. However, typically, even paint thickness is usually accepted only with 100% compliance with the minimum specified. Correction of paint thickness has often been required when only one spot was less than the minimum. Although section loss from corrosion may occur from inadequate painting, and thus inadequate painting can have a "downstream" effect on safety, the correlation to safety is not as strong as for other structural materials and components.

As indicated previously, QA as currently defined is primarily directed towards the construction phase of a project's life, including material testing of products used.

One survey question asked what parts of critical structural components are included in their agency QA programs. Table 1 summarizes the responses.

Only three respondents indicated that their QA programs do not include structures. However, most of the documents received do not include all the requirements of a formal QA program for structures, indicating that the respondents may believe that they are performing QA, but in reality they do not have a complete, formal QA program of documentation. The majority indicated that the more traditional materials, steel beams, prestressed (P/S) concrete beams, decks, and

TABLE 1 Coverage of various structural components in quality assurance programs

Does Your Quality Assurance Process Address:	Yes	No
Critical structural components?	28	3
Steel beam/girder fabrication?	29	4
Prestressed concrete beam/girder fabrication?	29	4
Concrete bridge decks?	24	6
Concrete substructure components?	23	7
Sign bridges?	20	12
Sign, signal, luminaire supports?	18	13
Foundations?	23	6
Timber structures?	21	9
Fiber-reinforced polymer components?	6	20
Bridge rails?	21	9

substructures, are included in their "structures QA" program. QA for cast-in-place concrete in decks and substructures is much the same as for nonstructural components. Existing QA for the materials should therefore suffice, but QA for combining these materials into "components" needs to be strengthened.

Although many manuals were received for steel and concrete bridge material or components, virtually none were received for sign bridges, foundations, timber, or bridge rails. Because these components are usually constructed from steel or concrete, their material requirements could be construed as being covered by the other manuals. Again, this does not satisfy the requirements of a true QA program.

Florida's *Manual for Quality Assurance of Precast Prestressed Concrete Members* (and other similar manuals) provides an excellent example of a QA manual for this particular structural material/component. The manuals received for P/S concrete and structural steel could be used to develop a model QA manual for all components. However, these manuals have one common deficiency in that they do not clearly differentiate between QC, VS&T and/or IA testing locations, and/or testing frequency for the various materials. This is specifically true for steel fabrication, where most indicate that the AWS D1.5 *Bridge Welding Code* is the basis for their QA program, although the code is really a QC document.

As would be expected for new materials, specifically FRPs, the majority responded that this is not covered by their QA program for structures. Although six respondents indicated that FRPs are covered, no specific requirements for this material were received.

Another question asked, "Does your QA program include requirements relating to structural components for:" and listed the various structural materials. Table 2 summarizes the responses.

As might be expected, all respondents indicated that materials are included in their QA programs. However, unexpectedly, approximately one-quarter indicated that construction is not. Only 18 respondents indicated satisfaction with their QA programs for design and construction. Approximately 9 in 10 respondents reported that plant certification is required for steel components, with about 80% requiring plant certification for P/S concrete components. Most transportation agencies use the existing American Institute of Steel Construction (AISC) and Precast/Prestressed Concrete Institute (PCI) industry certification programs as the base requirement, often mandating that proof of this certification is necessary to be considered qualified to bid. Approximately three-quarters of the respondents indicated that certification is required for sign structures, although specific QA requirements for sign structures, other than for the generic materials, were not submitted. Although current certification procedures have weaknesses that need to be corrected to allow full confidence in certified fabricators of any material, plant certification is considered a very important part of assuring QA for structural components. This will be discussed later in the report. Connecticut indicated that they have two trial projects underway, with a formal QC/QA program being developed and implemented.

The types and frequency of tests for materials reported by the respondents is typical for all material testing and most, if not all, are adequate. However, the question still exists as to whether the testing being done is QC, VS&T, or IA.

Fabrication plant testing parameters varied from a requirement for full-time state personnel to be present to essentially end-of-line acceptance. These extremes both have their pros and cons. Full-time inspection is costly and subverts the purpose of a QA program, because state inspectors either end up doing QC inspection or only witnessing QC inspection and calling it VS&T. VS&T requirements for fabrication of steel and P/S concrete girders are generally referenced to applicable codes such as AWS D1.5. As stated previously, this is really a QC code, and supplemental VS&T and IA tests and frequencies need to be established.

Test requirements and the required frequency of testing are reportedly in state standards, although there are redundancies in the standard specifications used to control QA of structural materials. For example, some states include specific material requirements for structural steel, the purpose being that no changes will be accepted until the state reviews the requirements and indicates its concurrence by revising its own standard. Material requirements are also included in AASHTO documents and in American Society for Testing and Materials (ASTM) specifications and therefore do not need to be repeated in individual state standards. This

TABLE 2 Material and plant certification information from questionnaire

Does Your Quality Assurance Program Include Requirements Relating to Structural Components for:	Yes	No
Materials?	33	0
Fabrication plant certification?		
Steel?	32	3
Prestressed concrete?	28	7
Miscellaneous (sign bridges, luminaire/signal/sign posts)?	23	9

redundancy increases the probability of conflicts and slows adoption of new technology as the state standards go through the typical review/assess/rewrite/approve/reprint process. Considering the collection of individual state steel construction manuals versus the AWS D1.5 *Bridge Welding Code* is a case in point, wherein acceptance of AWS by reference might expedite the integration of generally accepted innovations.

One area of concern to industry partners is timely decision making. This is particularly important for production line operations such as steel or P/S concrete girder fabrication. Only seven respondents indicated that their field personnel have authority to determine substantial compliance (where the definition of "substantial compliance" may vary from state to state, but in general indicates that inspectors can accept work, but perhaps not allow exceptions). Lack of decision-making authority at critical stages of fabrication and construction by on-site personnel can seriously affect production schedules. Such impacts must be recognized by all parties in a project, because without such recognition the teamwork concepts so essential for success could be eroded. Two states indicated that a time limit for decision making was included to avoid delay costs.

The decision-making authority varied from the project engineer to central office personnel, and was usually the state bridge engineer. The potential for project delays increases significantly as level of decision authority is moved higher. Project personnel should be adequately trained to make most, if not all, decisions affecting timely construction. For complex projects, a structural engineer familiar with the design requirements should be assigned to the project to assist the project engineer. This was done for the Woodrow Wilson Bridge deck replacement project in the Washington, D.C. metropolitan area, and it allowed reasonably quick decisions to be made that contributed significantly to the early completion of the project.

States were also asked about certification of fabricators for steel, P/S concrete, and miscellaneous structures. Thirty-two of the 35 respondents indicated they require AISC steel fabricator certification, and 28 of 35 noted that PCI certification is required for P/S concrete. These industry-sponsored certification programs require that the fabricators have a QC plan. Responses to a subsequent question relating to the prime contractor revealed that only 12 of 31 were required to have a QC plan. For a QA program to be complete, the contractor's QC plan should incorporate and complement the fabricator's QC plan.

Twelve respondents indicated that they provide minimum requirements for the contractor QC plans, but no examples were submitted.

A review of state responses to the question asking for a determination of how many would accept critical structural materials by certification, and presumably with minimal VS&T and/or IA testing, shows that the states accept certificates of compliance for those items for which they have the most experience (for example, steel, concrete, and admixtures) and that have a track record of proving satisfactory. However, even for many of the very traditional materials (for example, paint) many transportation agencies do not accept certificates.

Only three states noted that they accept FRPs under certification. Acceptance by certification should increase as FRPs become more widely used, largely because the specialized test equipment is not available in the standard highway laboratory. The use of FRPs is still in its infancy, and design criteria, performance requirements, etc., are still being developed. The ASTM has developed specifications for some structural items using FRPs (*13*). Specifications exist for plastic lumber (ASTM D6109, D6111, D6112, and D6341) and mechanical fasteners in plastic lumber (ASTM D6117). FRPs are being used in bridges and railroad ties. Lampo (*13*) notes that there are other applications for FRPs and that use of this material will become more commonplace in the near future. NCHRP Project 4-27, "Application of Fiber Reinforced Polymer Composites to the Highway Infrastructure," is expected to address the issue of QA (and QC) needs for these materials, and NCHRP Project 10-59 is specifically developing QA for bonded FRP concrete repairs.

In January 1999, a new directive mandated that all bridges in the United Kingdom be able to handle trucks weighing up to 40 Mg. The capacity of a bridge built in 1874 that was failing at 7.5 Mg was increased by four plates of P/S carbon-fiber-reinforced polymer, which were applied to each of the eight innermost cast iron beams for both spans using structural adhesives to affix the plates at the anchor points and to bond the plates to the soffits. All this occurred while the bridge remained open to traffic (*14*). If such FRP retrofits become commonplace, it will be necessary to have QA processes in place that are at least equivalent to those available for traditional retrofit methods.

NCHRP Synthesis of Highway Practice 102 (*15*) provides a complete summary of the state of the practice relating to material certification as of 1983. Once again, the study is primarily for pavement materials, although portland cement concrete and reinforcing steel, which are both found in critical structural components, were included. For "manufactured products," the study included signs and structural concrete. The report notes:

> The success of a certification system depends first on the ability of the specifying agency to establish the validity of the certification. The agency must be in a position to do this by independent random sampling and testing of the material carried out by its own staff and laboratory or at least an entity of its choosing that is completely independent of the normal quality control testing and certifying procedures carried out during production.

This synthesis concludes:

> Acceptance of materials used in the construction and maintenance of transportation facilities on the basis of certification of the manufacturer is a device that can be employed successfully by specifying agencies. Where it is properly conceived and implemented it can prove to be cost-effective through the elimination of redundant testing and the avoidance of construction delays caused by the time required for sampling, testing, and evaluation. Certification acceptance can be conducted in such a way as to provide the owner with assurance that the items so covered are the quality specified.

The findings of this report are still valid today, and certification by acceptance should be a major goal for structural materials and components as resources dwindle and the pressures to eliminate redundant testing and procedures are increased.

Twenty-seven of 32 questionnaire respondents indicated that they do VS&T of the materials accepted by certification. However, the list of tested materials submitted was not as comprehensive as those included in the survey question, indicating that only one or more of the materials listed are tested as a part of VS&T. To develop true QA procedures, each material has to be addressed separately, with those that can be accepted with confidence under a certification process separated from those that cannot. Individual states may have different experience levels in the acceptance of different materials—implying that information sharing is important.

Recently, "cross-state" acceptance/testing, which allows a contractor/fabricator to submit certification from other states as full compliance to the state in which it is doing work, has been championed. This is already done for some products in regions where state consortiums have been formed. For example, in the mid-Atlantic region, six agencies have been involved with a regional Structural Committee for Economical Fabrication. This group has developed procedures allowing paint left over from one state's project to be used on another state's components without further testing. This provides economies to all—fabricators do not have to dispose of left-over paints, which can be a hazardous waste, and the states get the benefit of lower bids with the allowance to use up this paint supply. Other regions have formed similar groups that are working towards similar goals. Refocusing these groups towards the development of QA program components could be highly beneficial.

AASHTO documents have always placed a strong emphasis on materials testing. Specifications for structural materials are well known and available to both owners and contractors/fabricators. They appear primarily in the AASHTO material specifications and/or the ASTM specifications. These specifications are often supplemented by modifications that appear in the state standard specifications or special provisions. Two problems that affect optimizing a QA program are the existence of dual (AASHTO and ASTM) specifications and the use of "supplements" on the part of individual owners. Dual specifications will often have different requirements. State supplements are "thumbprints" that are issued for a particular state's projects based on their perceived needs for additional or modified requirements. One standard is the AWS D1.5, *Bridge Welding Code*, which many states do not use without modifications. One state has even written its own steel fabrication document. These individual modifications to the AASHTO standards, and the need for both AASHTO and ASTM material specifications, should be examined carefully to determine if it may be desirable that they be included into a single set of national standards. Fabricators and contractors, particularly for major bridge type projects, operate in many states. Having to customize their operations for different clients adds cost and work.

A key to use of specifications, and QC/IA/VS&T, is the proper use of statistical analysis of the test results. *NCHRP Synthesis of Highway Practice 38* (*16*) summarized the proper relationship of statistically based specifications to assurance of quality. This report notes, "The initial step in drafting a complete, statistically based acceptance plan is to define good and poor material or construction techniques. In general, 'good' means that the average quality is such that there is no question as to purchase at the full price. 'Poor' means that the average quality is such that it is not acceptable for the intended use." Note the use of the term "average quality." For critical structural components, this is a crucial decision. Can less than 100% be accepted for butt welds in tension members of failure critical members? The answer has to be yes, because statistically we can never find 100% of the flaws. Historically, acceptance has been based on the correction of 100% of those flaws that are discovered during the QC and/or VS&T program. A more complete investigation of this issue would focus on the effects of statistical analysis vis-à-vis the reliability index for the structural component, and on selecting an appropriate reliability index compatible with the LRFD bridge code.

These questions were intended to determine the state of the practice for QA during construction of structural components. They relate to materials before and during incorporation into structural components, but do not cover erection (e.g., of girders) or placement (e.g., of bridge decks) during construction (see FHWA Technical Advisory T 5080.12, "Specification Conformity Analysis").

The FHWA has issued a Technical Advisory, T 5080.16, "Development and Review of Specifications," dated August 7, 1992, to provide guidance for the development and review of specifications. However, interpretation of these requirements has led to wide variation in the various state specifications.

In-Service Phase

As is indicated in the discussion on design impacts on QA, maintenance or items occurring after construction have a relatively small affect on the quality/cost of structures. *NCHRP Report 422* (*10*) calls this "quality management" rather than "management of quality," which seems to better fit the definition of QA. This report discusses maintenance needs in terms of level of service (LOS), which is a measure of riding comfort for the traveler, with one of the requirements being related to

> . . . refocusing the direction of their maintenance operations [to]
>
> - Determine the LOS expectations the traveling public is willing to pay for and assure them that the agency is meeting those goals,
> - Develop the funding level needed to achieve a desired LOS,
> - Develop a 'priority strategy' to direct maintenance operations during periods of less-than-full funding,

- Achieve a uniform LOS throughout the agency by identifying excessively high or low areas of maintenance, and
- Identify areas requiring additional employee skills or equipment to accomplish assigned tasks.

This same list, with minor changes, could be applied to quantifying the needs for a QA program for structural materials and components. One such change could be to note that there are LOSs for bridges—primarily those associated with being able to safely carry traffic in a manner such that there is not excess congestion. If bridges collapse or there are undue user delays from bridge reconstruction or deterioration, the traveling public loses confidence in the entire highway system, and this loss is not limited to the agency owning the structures in question. Thus, the QA system must be complete and uniform across agency boundaries. This is a significant part of what bridge management systems (BMSs) are intended to provide (for more information, see references *17* and *18*). The initiation of a BMS (including bridge inspection) on the part of agencies is a means of receiving advance warning of safety defects or other bridge conditions (including traffic counts) that will affect the LOS of structures. With regard to safety, as the inspector's evaluation of structural condition changes, the agency, through the BMS, will be able to determine when the LOS no longer meets the safety demand for either traffic volume or weight-carrying capacity, flagging the need for funding and other activities. Properly implemented, the BMS will also provide strong feedback to the design function, indicating those items that should be changed for future designs to prevent recurrence of problems.

Specific issues that are related to LOS that should be addressed with QA issues are performance limits for various structural conditions, load capacities, and acceptable geometrics depending on the roadway class.

The environment to which the structure will be exposed when developing project-specific QA plans must also be considered. For example, the FHWA reports "However, examination of the data obtained in this study indicates that these traditional 'quality' indicators (water-to-cement [w/c] ratio; consolidation; air content; etc.) are far overshadowed by the degree of severity of the environment to which the concrete is exposed" (*19*). Although this was written specifically about P/S concrete bridge components, it is equally true for steel (and other materials), as is documented in a report by the American Iron and Steel Institute (*20*) for uncoated weathering steel bridges. In most cases, "micro-environments" rather than "macro-environments" affect the ultimate performance of concrete and steel structural components. Structures near a seacoast are in marine environments that are the primary macro-environments that cause premature distress. Structural materials and components beneath bridge joints are in micro-environments. Although traditional QA procedures require essentially the same material properties and testing for all environments, the designer has to be aware of the environmental affects of macro- and micro-environments and incorporate only proven details and material properties at these locations.

NCHRP Project 12-43, "Life-Cycle Cost Analysis for Bridges," is directed toward developing a financial management tool. It could be used to compare the performance of bridge structures of different materials and components in different environments, providing a quantifiable basis for material selection.

QUALITY ASSURANCE OF COMPONENTS

Fabrication

Many of the defined critical structural components are "manufactured" at sites that are remote from the construction location. These include steel and concrete (precast and P/S concrete) girders, sign bridges, bridge joints, and railings. Therefore, to provide confidence in the quality of these products when they are received at the job site, inspectors are assigned to the manufacturing locations, at substantial expense to the owner. Is this expense cost-effective or is there another way to ensure quality? These products are essentially "finished" components when they arrive at the construction site; therefore, inspection at that time is often not possible. The traditional means of accepting these components is for a shop inspector to place a "stamp of approval" on the piece prior to shipment. Job site inspectors then verify the presence of this stamp and incorporate the component into the project without further inspection, which would require specialized equipment. Great faith is placed in the plant inspector's stamp of approval and, in turn, the fabricator's QC process. This approach also assumes that no significant damage to the structural component occurs while it is being transported to the project site.

With reduction in personnel occurring in many sectors, plant inspection is being questioned as to its cost-effectiveness, the trade-off being reduced cost versus possible reduced confidence in quality. There are alternate ways to overcome some of the concerns should in-plant inspection be reduced.

Each state normally has full-time inspectors located in local fabrication plants. These inspectors could perform VS&T and IA inspections for other states if agreement were reached as to minimum and common QA requirements. Significant improvements in many of the existing industry certification programs that are required for shops would also add to the confidence level.

Traditionally, shop drawings are submitted to the owner (state) for review and approval (or acceptance), but usually disclaiming any responsibility for accuracy. This practice provides some assurance that the design is "buildable," and uncovers any dimensioning errors in the design documents. In addition, it can indicate that there is a general accuracy in the numbers (dimensions, member types, etc.) and that there have been no departures from specification requirements.

Therefore, shop drawing review by the state can be more of a VS&T review of the design documents, not a part of the fabricator's QC. Although fabricators may need shop drawings for their own QC, the requirement to submit them to the owner does result in expense to the fabricator. This is because of detailed requirements in the standard specifications and the time lost during the review and acceptance process. With the increasing use of computer-aided design and drafting (CADD), the ability exists for shop drawings to be automatically developed by the fabricator if the designer's CAD/CADD files are a part of the bid documents in addition to the design drawings. This could be studied to determine feasibility and potential savings to all parties.

However, this does not mean that the fabricator would not have a responsibility to disclose discrepancies. Section 4.3.2, *Review*, of ISO 9000 states "before submission of a tender . . . contract . . . shall be reviewed by the supplier to ensure that: a) the requirements are adequately defined and documented . . ." Although this is also true in the United States, fabricators can find it difficult to refer to perceived errors prior to bidding (because of time pressures on bid development) and, if they do point out errors and the differences cannot be resolved, fabricators are left with the choice of not bidding, including the cost of correction in the bid and risking not having the low bid, or gambling that the error will be corrected and bid prices adjusted as needed. However, if fabricators assume that the error will be corrected with adequate price adjustments, there is the risk that a sought-after price adjustment may be declined, with the fabricator left with the option of defaulting or losing money. Better definition of the responsibility for these types of errors is necessary to ensure a quality product, particularly when bid costs are affected.

On the other hand, many fabricators improve bridge quality by making suggestions on bridge changes—often with any additional money requirements. Many fabricators consider it useful to point out errors so that they are not left attempting to build the unbuildable. Such feedback from fabricators provides assistance in the QA for the states.

Industry Certification Programs

The following are certification programs administered by industry in the United States for various structural materials/components at this time:

- The PCI Plant Certification Program as administered by the PCI. Group B includes bridge-related products and has four subparts:
  - Precast Bridge Products,
  - Prestressed Miscellaneous Bridge Products,
  - Prestressed Straight Strand Bridge Members, and
  - Prestressed Draped Strand Bridge Members.
- The AISC Quality Certification Program as administered by the AISC. There are two subparts that relate to bridges:
  - Major Steel Bridges; this also has a fuzzy C-means (FCM) rider, and
  - Simple Steel Bridges.
- The Shop Painting Certification Program (QP-3) as administered by the Structural Steel Painting Council (SSPC).

In addition, the AISC has initiated an erection certification.

Questionnaires were sent to the AISC, PCI, SSPC, Portland Cement Association, American Segmental Bridge Association, and American Institute of Timber Construction. The industry questionnaire was designed to elicit an industry perspective on the merits of their programs. An additional purpose was to obtain the details of their programs as they relate to the QA of structural components. PCI and SSPC have formal certification programs, and copies of the requirements and details were furnished for information. Both groups indicated that their definition of QC agrees with the AASHTO definition. The SSPC program covers painting of steel. The PCI program covers items involving P/S concrete girders, precast concrete bridge decks, precast concrete substructures, precast concrete signs, foundations, and rails. Neither program provides for warranties of the work, although the SSPC indicated they believe that they can add to QC/QA. Both indicated that incentive/disincentive (I/D) clauses can also be used to improve QA, but the PCI noted that much work is required to establish applicable qualities. The PCI does not believe design/build by itself is adequate to ensure quality—warranties or performance criteria are necessary as well. The SSPC requires a "certificate of training" from an established training provider for the supervisor or 10 years of experience. The QC supervisor must have 3 to 5 years of experience, and inspectors 2 years and documented training. The PCI has a formal three-level certification program. Level II is required in the plant. The SSPC and PCI invite input from owners into their program, although the PCI notes that only Texas has participated. The SSPC uses a consensus approach and obtains input by correspondence. Both programs require a formal QC plan [PCI calls it a Quality System Manual (QSM), which was required by December 31, 2001] to be in place, but both groups indicated that they release it to owners only with the permission of the contractor or fabricator. The PCI indicated that they "encourage owners to require submittal of the plant QSM." The SSPC performs audits "at least annually" with the "prerogative" of unannounced visits, whereas the PCI stated that two or three unannounced visits are conducted per year. Neither the SSPC nor the PCI releases audit findings to owners, although both indicated that it may be possible. Both allow owner's representatives to accompany the audit team, but only with fabricator/contractor permission. Both programs are continually seeking improvements; the PCI believes that full implementation of their QSM requirement will be a giant step forward. Interestingly, the SSPC does not believe that end-of-line testing alone is adequate, whereas the PCI does. The PCI noted that 80% of its work is in the private sector where there are no outside QA requirements and their product success speaks for itself. The PCI noted that some states still have very restrictive, prescriptive specifications that prevent producers from taking advantage of new technology and materials, and these states continue to use design and construction details that have proven to be poor performers.

The industry questionnaires confirmed many of the concerns expressed by owners as to the credibility of those programs and their willingness to accept them as the only requirements for proof of capability to produce quality components. Part of the reason for this is related to the industry, but much of it is caused by the owner's requirements and a reticence on the owners' part to work with industry to implement new technology and/or to find ways to do business in a timely and less expensive manner.

Although the contract documents of many states require fabricators/producers/painters to be certified prior to the award, many perceive these programs to be of questionable value. It is widely believed that if fabricators pay their dues by going through appropriate processes or by performing adequately, certifications will be automatically awarded. For states to have more confidence in these programs, they must meet the states' expectations. Some of the concerns and comments on these expectations are included here and may not be applicable to all.

- The fabricator QC program required by the certifying group does not have to be shared with the bridge owner. Thus, the owner does not know what is included and must implement full (QC + VS&T) testing.
- The industry "audits" are pre-announced to the fabricator to give them time to prepare.
- Owner personnel are not invited to participate in the "audit."
- Certification may be awarded without concurrence of owners.
- There is no explicit provision for owner input into the industry requirements.
- Emphasis is placed on fabricator efforts (e.g., shop drawings and administration) rather than items that will improve confidence in the quality of the finished product. Audit results are not available to owners who may have work underway or planned for a particular shop without the fabricator's permission.

Correcting these perceived deficiencies would allow more confidence in the certification program and subsequent acceptance of the QC efforts and reduced owner QC inspections. It is suggested that a task force be set up to establish minimum requirements for industry certifications and perform audits independent of any industry audits.

Construction Issues

Bridge decks and other reinforced concrete components, including foundations, are structural components built on-site. Different levels of QC, VS&T, and IA functions occur at this level. VS&T and IA testing must be redefined for construction stage activities to ensure confidence in the product. Many of the activities are such that they must be observed to ensure they meet the project minimum specified requirements. There is no actual testing done as there is for the materials from which the components (e.g., foundations or finished girders) are constructed. For example, pilings cannot be easily inspected for length or capacity after being driven, although the material itself (steel piling, concrete, reinforcing bars, etc.) may have passed all of the prescribed material testing requirements. Questionnaire responses indicated that 7 of 31 state DOTs do not include requirements for structural components in their QA programs.

An example of the need for QA during construction that goes beyond basic materials testing would be for placing concrete bridge decks. Many states require a curing compound to be applied to freshly placed concrete to ensure its durability over the deck's design life. Twenty-six states accept curing compound by certification and most likely perform independent IA testing as well. However, for this material to be effective, it must be applied in the proper amount, which is usually specified as a given number of square feet per gallon (m^2/L). Although the material may be pigmented to allow visual detection of its presence, the application rate cannot be determined after it is in place, nor can it be determined if it was applied at the proper time (immediately behind the screed). Proper training of the individual actually spraying the curing compound is as essential as proper training of inspectors.

Proper handling, placement, erection, bolting, etc., of the materials and their proper incorporation into the finished components in accordance with the specification requirements is essential to ensure that the 75-year design life is achieved. Improper erection can result in built-in stresses that were not considered during the design; improper bolting techniques allowing joint slippage and deformations not intended; inadequate substructure (bearing capacity, piles, etc.) preparation that could cause structure settlements or collapse; and improper curing of cast-in-place concrete elements that will reduce service life causing excessive maintenance. The results of inadequate construction techniques will not show up for many years, and the cause probably cannot be ascertained even when the deficiencies appear. Warranties, guaranties, and certifications of compliance are unenforceable after such extended periods.

A comprehensive QA program must include materials testing, inspection during installation, and documentation of construction stage activities to ensure that the "minimum specified" structure is provided. A QC/QA program that relies only on documentation of material testing frequency and statistical results is not sufficient for structures. A statistical approach to construction activities may allow less than 100% presence of owner inspectors and still provide an acceptable risk. Table 1, "Acceptable Buyer's and Seller's Risks," of *NCHRP Synthesis of Highway Practice 38* (*16*,

p. 8) provides guidance on determining test frequency for a variety of materials. A similar approach, but determining risk based on the ramifications of less than adequate construction, may allow relief from full-time inspection. Items such as piling would be "critical" items and risks would be high for the buyer because inadequate pile length could result in structure collapse, particularly for scour critical situations. Full-time inspection by the owner may be warranted for these high-risk items. On the other hand, bolt installation for girder splices may have a lower risk factor because improper installation would result only in unaccounted deformations that potentially pose minimal, if any, structural risk and, accordingly, warrant only periodic VS&T. This approach would work only with an adequate contractor's QC plan and properly trained QC inspectors.

Collaboration

Recently, the public and private sectors have joined together to address many items of common interest that will enhance the quality of structural materials and components, reducing the costs to both parties by providing uniformity of application of specifications. This group is known as the AASHTO/NSBA (National Steel Bridge Alliance) Steel Bridge Collaboration. The group has developed regional and specialty working groups to address many specific concerns, one of which was the need for a *Steel Bridge Fabrication QC/QA Guide Specifications* manual (*21*). This document incorporates a requirement for AISC certification, "or as determined by the owner," as a base requirement for any fabricator. It covers minimum personnel qualification requirements for both fabricator (QC) and owner (QA), as well as equipment requirements and other associated items. It is considered a good base on which to build a comprehensive model QA plan for steel fabrication. However, it does not address the design or the service life portions of the product. Similar efforts for other materials could be as productive in better assuring QA for critical structural materials and components.

The AASHTO/NSBA Steel Bridge Collaboration has also developed a document for shop drawings (*22*). Additional guidance is available on QA for steel structures in Section 8 of AISC's *Code of Standard Practice for Steel Buildings and Bridges* (*23*).

PERSONNEL AND LABORATORY QUALIFICATION, CERTIFICATION, AND ACCREDITATION

Personnel

A key element in all of the efforts and resources devoted to QA is the inspector, and in particular the owner's inspector, who is the engineer's representative. Texas succinctly expressed the proper role of the inspector in Appendix G of their *Manual of Structural Steel Inspection*, where it states what is important in successful QA for all structures—a working relationship between the inspector and the fabricator (or contractor), and whether the inspector is in-house or a consultant, and regardless of the material.

This type of relationship is necessary to ensure the minimum requirements of the specifications and thus achieve QA. Its value in the overall success of a project cannot be overstated, because project bids may come in lower if the contractor knows they will be treated fairly, and contracts are completed on time as cooperation resolves uncertainties in the plans and specifications.

States were asked if their QA programs included requirements relating to testing and inspection personnel and laboratories. Thirty-one of 32 responses indicted requirements are included for in-house personnel and laboratories, but only 23 include requirements for inspection consultants or independent laboratories.

In-house VS&T of materials appears to be practiced by most if not all of the respondents. Alaska indicated the use of contract personnel for all VS&T inspections. Twelve states use both in-house and contract inspectors, whereas 10 states perform all inspections with in-house personnel. Two states indicated that they bill costs to the contractor for out-of-state inspections, such as those at fabrication plants. Many states have personnel stationed at fabrication plants during the fabrication period for their work.

All respondents indicated that they require verification of conformance at critical stages of component fabrication, although responses to one survey question indicated that most often any deviation has to be resolved at higher office levels, potentially resulting in time delays.

One state that requires full-time shop VS&T inspectors has a policy that state personnel cannot travel on weekends, thus forcing inspectors to show up late on the first workday of the week and to leave early the last day. This often means that the fabricator has to delay until the inspector arrives before proceeding with critical stages of work, thus negatively affecting production schedules. This adverse impact on production is magnified if fabrication is on a 7-day, multiple-shift schedule.

There are numerous programs available for certification of QC and QA personnel. Many of these programs are industry sponsored. Some are in-house programs sponsored by state agencies. The AASHTO *Implementation Manual for Quality Assurance* (*1*) states that, "All persons directly participating in acceptance activities must be qualified sampling and testing personnel for their assigned responsibilities. Only qualified laboratories will perform the required tests." Regulation 23CFR209 requires "all sampling and testing data to be used in the acceptance decision or the IA program . . . be executed by qualified sampling and testing personnel." Regulation 23CFR203 defines qualified as "Personnel who are capable as defined by appropriate programs established by each SHA [state highway agency]." Responses indicated that a significant number of states do not require testing personnel to be certified for state, contractor, and testing laboratories.

Many states indicated that they use in-house programs for their own personnel. Most require contractor personnel to meet other certification requirements, such as the National Institute for Certification in Engineering Technology (NICET), American Welding Society–Certified Welding Inspector, PCI, and the American Concrete Institute (ACI). Brief descriptions of some of these are provided here.

The NICET program, established by the National Society of Professional Engineers through a grant from the FHWA, provides a system of examination and classification through which personnel may be certified at several levels of competence. They provide certifications in Transportation Engineering Technology as follows:

- Bridge safety inspection,
- Highway construction,
- Highway design,
- Highway maintenance,
- Highway materials,
- Highway surveys, and
- Highway traffic operations.

For steel fabrication, most states require AWS certification requirements. The AWS D1.5 *Bridge Welding Code* states that

> All Inspectors responsible for QC and QA acceptance and rejection of materials and workmanship shall be qualified as follows: (1) The Inspector shall be an AWS-Certified Welding Inspector qualified and certified in accordance with the provisions of AWS QC1, *Standard for Qualification and Certification of Welding Inspectors* . . . Personnel performing nondestructive testing shall be qualified in accordance with the American Society of Nondestructive Testing (ASNT) *Recommended Practice No. ASNT-TC-1A*, or equivalent.

(The ASNT-TC-lA program provides for three levels of certification for each type of nondestructive testing.) Note that the AWS requirement applies to both QC and QA inspectors; however, as indicated, many states do not require their inspectors to be certified. In addition, as indicated earlier, most states incorporate the *Bridge Welding Code* as a part of their contracts.

Although conformance with the AWS training requirements would seem to provide adequate QC/QA confidence, the ASNT-TC-IA program has been questioned. Hellier (*24*) points out that

> ASNT-TC-IA's greatest weakness is that far too many employers have abused the flexibility of the program. Consequently, there is no way to provide assurance that every employer's program meets the intent of ASNT-TC-lA. In fact, the nature of ASNT-TC-lA permits the opportunity for self-certification and other practices that could be considered questionable.

He notes that the rest of the world moved forward with internationally recognized programs, many of which are based on ISO 9712, *Nondestructive Testing—Qualification and Certification of Personnel*. Some states (e.g., Texas) have a hands-on test that is required in addition to ASNT Level II certification.

The PCI also has a Quality Control Personnel Certification Program that provides a three-level certification process. The PCI provides two training manuals for each level if in-house training is to be provided. According to the PCI, 28 states "accept or require" PCI Plant Certification (*25*).

The Portland Cement Association (*26*) offers programs for the training of sampling and testing personnel. Examples include a series of training videotapes covering various concrete testing requirements and "Fundamentals of Quality Concrete." The "Contractors Guide to Quality Concrete Construction" seems especially pertinent for training purposes.

The ACI has a certification program for almost every aspect of concrete construction. Kansas noted that approximately one-half of their construction inspectors are ACI certified.

The FHWA, through its National Highway Institute, also offers many training courses directly related to the quality of structures, including many in the design area.

Although these programs may provide adequate training for materials assessment, they may not provide by themselves QA for finished critical structural components. QA for the finished members requires experienced professional judgment as to the adequacy for purpose. Technicians often cannot provide this professional judgment. There also needs to be a close tie between the materials inspection and fabrication inspectors/testers and an engineer knowledgeable the product's service-life-performance requirements.

Testing Laboratories

Thirty-one of 32 respondents indicated that their in-house laboratories are included under their QA plan. Approximately one-third of the respondents reported that requirements for inspection consultants and testing labs are not included. Under Regulation 23CFR637.209, all state central laboratories involved with NHS project testing are required to be accredited under the AASHTO Laboratory Accreditation Program (or equivalent) prior to June 30, 1997. In addition, 23CFR209 set a deadline of June 29, 2000, for all laboratories to be qualified for sampling and testing materials used on NHS projects, and this includes contractor test laboratories used for QC. "Qualified" is to be defined by each state, but must include provisions for checking test equipment and has the requirement that the laboratory keep records of calibration checks. Laboratories must possess the necessary equipment, properly calibrated, in addition to trained personnel.

The AASHTO Accreditation Program is provided to ensure that proper testing is being done at laboratories. This program uses laboratory assessment and proficiency sample services provided by the AASHTO Materials Reference Laboratory and the Cement and Concrete Reference Laboratory (CCRL). The CCRL includes a Laboratory Inspection Program and a Proficiency Sample Program. The Laboratory Inspection Program of the CCRL is limited to cement,

cement quality system, concrete, aggregate, steel reinforcing bars, and pozzolan. The Proficiency Sample Program offers programs on portland cement and concrete, plus other nonstructural materials. Thus, the current AASHTO materials programs do not address structural materials other than basic materials testing of steel, concrete, and its components.

NCHRP Synthesis of Highway Practice 263 (Appendix E) (*3*) lists the materials for which each state laboratory is accredited. Other than portland cement concrete, structural materials (e.g., structural steel, reinforcing steel, and aluminum) are not included. This report also notes some concerns with consulting testing, such as timeliness and accuracy, but indicates that such concerns rarely arise. It is worth noting that such concerns would be present occasionally among any large groups, including in-house state DOT laboratories.

As a result of a congressional mandate, the National Institute of Standards and Technology was asked to review laboratory accreditation in the United States to see if the existing accreditation system is a major impediment to U.S. trade (*27*). The result was the formation of a not-for-profit corporation called the National Cooperation for Laboratory Accreditation (NACLA). Representatives from Canada and Mexico are included. Participation is voluntary, but it is anticipated that most federal agencies, major industries, laboratories, and accreditors will eventually become members and adhere to the NACLA system. This system is intended to be fair and open, and could be a model for solving conformity assessment issues as well as other industrial and technological problems.

ALTERNATIVE MEANS TO ENSURE QUALITY ASSURANCE

There are many alternatives to the traditional design/bid/build process used for construction projects that could affect QA. These alternatives are intended to enhance quality, reduce costs, reduce personnel, and/or reduce testing. Each has advantages and disadvantages. None is the panacea for QA problems and they must be considered on a project-by-project basis. This section provides brief summaries of some of these alternatives.

Warranties

Warranties are becoming more common for highway-related items for which performance can be measured in relatively short periods of time (approximately 5 years), such as paint on steel girders or asphalt pavement (*28,29*). However, very few states accept or require warranties for structural components, because quality deficiencies show up only after long periods of time (perhaps 20 years). Bridges and other highway structures are not ordinarily like computers and light bulbs, for which defective units tend to fail very early and the remaining population have a very long life. If the defective units fail early, such a product is well suited for warranties. However, if there is a more normal distribution of failures as a function of years of service, such that a significant number of critical structural components with defects can fail many years later, then warranties tend to be difficult to obtain and often are simply not practical or even available. Among the concerns with such time frames are that contractors may not remain in business, records are lost, etc. Under Regulation 23CFR635.413, "Warranty Clauses," the use of warranties for NHS projects is allowed for a "specific construction product or feature" subject to approval of the FHWA division administrator. Warranties are often issued by suppliers for products such as roofing shingles, where 25 years is common. Typically, these types of warranties are accepted by all agencies.

Paint is perhaps the most common structural item to have a warranty. The warranty period is generally quite short; 2 to 5 years for bridge paint. Russell et al. (*28*) note that

> There have been more warranties for bridge painting than for any other end product . . . Michigan . . . has required warranties on all bridge-painting projects since 1996. . . . One major reason why states are implementing warranties is to supplement their workforces and reduce the need for inspections . . . however, Maryland and Michigan still maintain 100 percent inspection on their warranted bridge-painting projects. Selecting the appropriate performance indicators and threshold levels is also important.

This last statement is a primary concern for structural components with an expected life of 75 years.

If a warranty were to be required for the contractor/fabricator of a steel welded girder, the designer may have to be a party to the warranty because, as stated previously, details incorporated into the design most often have the biggest impact on life span (e.g., fatigue cracking occurring in details that are known to be fatigue sensitive). This could be a complex issue to surmount.

Russell et al. noted that, "The general opinion of the state agencies interviewed is that warranty projects have proceeded satisfactorily and have been constructed with more care than usual. Workmanship on warranty projects appears to be better than under traditional contracting methods" (*28*). Twenty of 32 respondents did agree that warranties for structural components would enhance QA. The effectiveness of warranties is contingent on clear definition of the performance indicator and threshold levels of performance and assigning a warranty period equitable to contractors and owners. It is interesting to note that Ohio required warranties from manufacturers on a recently constructed, large-scale FRP bridge project. Additional discussion of warranties is provided in the section on design/build.

Incentive/Disincentive Clauses

I/D clauses have been very successful for reducing construction time for critical projects and for improving quality on pavement projects. I/D was used successfully for the redecking of the Woodrow Wilson Bridge carrying Route I-95 over the Potomac River, just south of Washington, D.C. For this project, the contractor earned more than $1.4 million in incentive payments by completing the project well ahead of schedule. Similar results (large incentive payments) were experienced in many other projects in the mid-Atlantic region in the 1980s. Each of these projects used anticipated traffic delay/detour costs in determining the amount of I/D payments. For projects where traffic volumes were very large, no one was willing to use the actual calculated costs because of the magnitude. By including large incentive payments with much shorter than traditional construction time frames, it is possible that the best and most efficient contractors ended up being the successful bidders.

Some concern was expressed about the quality of construction obtained when the contractor expedites construction, apparently only to obtain the maximum incentive payment. In contrast, on one very successful I/D project, the contractor stated that quality goes up, not down, since only the best personnel and equipment are assigned to these projects, because contractors cannot afford to do anything a second time. In addition, there was concern about the increased cost when the incentive payments are made.

FHWA Technical Advisory T 5080.10, "Incentive/Disincentive (I/D) for Early Completion," dated February 8, 1989, provides information on I/D contracts. The purpose of this technical advisory is "To provide guidance for the development and administration of incentive/disincentive (I/D) provisions for early completion on highway construction projects or designated phase(s)."

Performance-Related Specifications

One survey question asked if total reliance on "end-of-the-line" or "performance-related specifications" (PRS) alone is adequate assurance of quality for critical structural components. Only 8 of 28 respondents indicated that PRS or end result specifications (ERS) could be relied upon to ensure the safety of structural materials and components. Although PRS and ERS are two different approaches, both allow unsupervised work on the part of the fabricator/contractor, with full reliance on their integrity in supplying the product specified. As far back as 1976 it was reported that, "The greatest advantage of ERS to state agencies is the actual placing of responsibility for materials and construction quality on the contractor or producer. Other advantages are more complete, as-built records; statistically defensible acceptance decisions; and savings in engineering cost and technical personnel when all features are fully implemented." However, even with ERS there is a need for a comprehensive QA program involving spot-checking of the contractor's QC system. Some considered this to be a disadvantage of ERS, because they would have to have more highly qualified personnel than those employed for inspection duties.

West Virginia uses ERS for concrete mixes, where the supplier is allowed to reduce its cement factor (the reduced cost of cement is the incentive) when its statistical record of cylinder strengths (monitored as a plant output, not on a project basis) shows that the minimum required strength specified is being exceeded. This procedure could work for welding and other structural fabrication items, but will require monitoring of the output over many projects and with many clients by an independent organization.

NCHRP Synthesis of Highway Practice 212 (*30*) defines PRS as

> . . . specifications for key materials and construction quality characteristics (materials and construction factors) that have been demonstrated to correlate significantly with long-term performance of the finished work. They are based on quantified relationships (models) between such characteristics measured at the time of construction and subsequent performance. They include sampling and testing procedures, quality levels and tolerances, and acceptance (or rejection) criteria. Typically, they also include payment schedules with positive and/or negative adjustments that are directly related through the performance models to changes anticipated in worth of the finished work as a result of departure from the quality level defined as acceptable.

As a part of that effort, PRS related to concrete, steel, or timber structures, and structural materials, paints, and highway appurtenances were requested. Table 15 of that document shows that no responses on these items were received. One of the conclusions of *NCHRP Synthesis of Highway Practice 212* was to "Continue PRS research and development at the national level with emphasis on . . . including concrete, steel, or timber structures . . ." (*30*).

With critical structure elements and the materials from which they are made expected to have a service life of at least 75 years, whether PRS is applicable for many of these elements is questionable, because it is doubtful that meaningful models could be developed over this time frame for many materials. For shorter life elements, such as paint, it may be possible and should be studied further. *NCHRP Synthesis of Highway Practice 263* (*3*) notes that a major criticism of ERS and PRS is that they do not necessarily measure characteristics that are related to performance.

Design/Build

Design/build (D/B) is becoming a popular means of performing highway construction. Unfortunately, there does not seem to be a full understanding of the ramifications of this approach as it relates to quality, including the quality of the finished project or the necessary specifications. Under D/B, a team is formed (often combining the design and construction practitioners into a single unit) to design and build the project with reduced oversight, compared with traditional practices. However, this is about as far as the "rules" are specified for these projects. Hancher (*29*) states, "The concept (D/B) could be feasible for the successful implementation of warranties for highway projects."

A variation of the D/B is design/build/warranty (D/B/W) contracting, which is essentially the same as D/B, but a warranty is required after the project is accepted. L.G. Byrd, assisted by Albert A. Grant, developed a report for the FHWA entitled "Prerequisites for Successful Design/Build/Warranty Highway Construction Contract," sometimes referred to as the Byrd Report. The discussion for D/B/W applies to D/B except for the warranty portion. This report listed many concerns of designers and contractors for this type of contracting and it provided recommendations necessary for successful implementation of this technology. Primary recommendations were to develop a Model Procurement Code and Project Selection Criteria to reduce costs as different DOTs bid D/B/W contracts, and to determine types of projects suitable for this form of contracting.

New Jersey uses what is called Modified Design-Build (MD/B), because state statutes require selecting contractors based solely on lowest responsible bid (*31*). This means that New Jersey must provide more quantitative and qualitative information up front to interested bidders than would be necessary under pure D/B. With MD/B, the state prepares plans and specifications so that the design is approximately 30% to 35% complete. Under pure D/B, these would only be 5% to 25% complete prior to bidding. To offset the opportunity of maximizing innovation by the contractor team under pure D/B, value engineering (VE) is added to the MD/B project to overcome built-in inflexibility often caused by statutory restrictions. For VE to work, the owner must be receptive to cost-effective proposals that adhere to sound engineering practices, and must understand that the designer–builder is in business to make a profit, although the designer–builder must be willing to absorb additional risk to achieve that profit. In addition, VE must be expanded beyond only items that result in cost savings, such as improved quality. The goals set by the New Jersey DOT for its MD/B project are much like the goals for pure D/B:

- Shorten delivery time;
- Increase constructability;
- Transfer risk;
- Foster innovation and creativity;
- Reduce administrative costs; and
- Reduce changes, disputes, and claims.

Interestingly, the contractor for their first MD/B contract entered into a lump sum agreement with their design consultant after the contract was received.

The questionnaire results indicated that 12 states used D/B for 132 of 1,403 structures built from 1995 through 1998. When asked if D/B provides adequate assurance of quality for structures, there was an almost even split (11 yes, 12 no) in the responses.

A valid concern for D/B reflects the makeup of the teams. Usually the construction contractor is the "lead" in the contract. If the designer wanted to add conditions to ensure an adequate safety margin, but it reduces the project profit margin, would the contractor agree? Contractors and designers must earn a profit to stay in business; therefore, it is imperative that issues such as this be addressed in the contract with some form of provision for adequate compensation. As with traditional designs, there will always be unforeseen factors that affect the cost of the project. Another concern expressed by design professionals is the cost of preparation of preliminary plans necessary to even be able to place a bid.

Value Engineering

The AASHTO VE program is a process that allows contractors to propose changes to the project after the contract is let to incorporate different ways to build the job. Presumably, VE proposals can include changes that reduce cost and proposals that improve quality at the same (or increased) cost. Traditionally, only cost-saving proposals have been considered. The AASHTO Guide Specifications for VE, Section 104.14, states "Contract bid prices should be based on actual work rather than on VECPs (value engineering cost proposals) that are subject to Agency approval" and "Use only proven features that have been employed under similar conditions or projects acceptable to the Agency."

Generally, there is a provision for cost sharing of the VE savings, which is usually 50–50. This ratio of prescribed cost sharing makes VE even more unlikely to be used for most structural projects because

- A reduced cost must be realized;
- The cost reduction has to be significant enough to allow the contractor/fabricator to recover administrative costs for preparation of the VECP;
- Where alternate designs (e.g., P/S concrete vs. steel) are included, they generally will not gamble that the VECP will be accepted and lower the bid on their alternate of choice, even if very significant potential savings are submitted. The second low bidder may have had a VE proposal that would have reduced costs; however, it will not be considered under present guidelines;
- Most items, as discussed in the section on the need for a design QC/QA program, are small, and the potential VE savings cannot offset administrative costs or the impact of delays; and
- Improved quality without cost reduction is not considered sufficient.

As discussed earlier, a QA program that includes the design phase of a project is considered necessary. VE during design is a natural first part of the design QA program. State standard practices could be value engineered, and more than one alternative should be included for many details on each project. Details should be AASHTO standards. Nonmonetary VE proposals must be included in the design and construction VE effort.

The FHWA *Federal-Aid Policy Guide* (*32*) includes a chapter on value engineering. This chapter (Chapter 6) supplies guidance on the application of VE in the federal-aid program. They "strongly encourage" states to use VE throughout highway project development, design, and construction.

Alternate Designs

In the early 1980s, the FHWA initiated a requirement for alternate designs of bridges on the federal-aid system that had an estimated cost of more than $10 million. The requirement was initiated by the FHWA because of its concern that designs, in particular steel designs for long-span structures, were not cost-effective. Although alternates could be two designs with the same superstructure material, for all practical purposes the result may be a bidding war between steel and P/S concrete superstructures. The ability to review or prepare a second design does have an inherent QA aspect—the opportunity to see how design conditions manifest themselves differently in different materials, and thus also provide the potential for pointing out errors in design in either or both alternates.

The results of the FHWA requirements for alternate designs do point out that bridge costs can be reduced by refining design requirements without compromising safety or long-term performance. Providing a formal design QA program may enhance this benefit even further. However, it is not clear whether the biggest gain is in cost savings or in quality enhancement.

Alternate designs are no longer required by the FHWA; states can submit cost estimates and their recommendation on an appropriate design.

A + B Bidding

For A + B bidding, contractors bid on the cost (A) and the time (B) to complete the project, with the state-specified time as a maximum. Some members of the highway community have concerns about the effects of this approach on project quality. This does not seem to be borne out, at least based on anecdotal evidence. For example, the Texas DOT was faced with calculated road-user costs of $251,700 per weekday when planning the rehabilitation of the I-45 Pierce Elevated in Houston. The estimated construction cost for the project was $31.6 million. The bidding procedure used was A + B, with incentive payments for early completion. In only 125 weekdays, the delay costs would equal the construction costs. However, the state limited the incentive payment to $53,000 per day. "The success of the Pierce Elevated project was worth almost $5.2 million based on the road-user costs, but it cost only $1.6 million in construction bonuses . . . The project . . . was so successful that it had many Houstonians wondering why all construction projects are not done this way" (*33*). There is no indication that quality was compromised in any way.

Special Activities

States were asked to describe any other special activities performed to help improve quality that were not included in the previous questions and comments. Eleven responses were received. Arizona noted that they have a Value Analysis Program for major projects that includes a constructibility review, as well as a peer review of all aspects of the project components. Georgia performs nondestructive testing of all sign structure anchor bolts to detect fatigue cracks. Maine has undergone significant changes over the past 5 years that have improved their quality of materials. Minnesota, Kansas, Illinois, and Michigan note that training of in-house and consultant inspectors has improved the quality of their program. Minnesota, Kansas, New York, and Texas noted the use of in-house meetings between the various disciplines to improve quality, as well as meetings with industry (contractors and fabricators) to provide feedback on improvements.

Respondents were also asked for any other thoughts they may have on the use of the QA process for critical structural components. Only seven comments were received. Essentially, each one reiterated the need for continuous inspection during fabrication to ensure quality. Respondents did not comment on the other aspects of the total program.

Building Industry Activities

One source of information for QA practices is the building industry. Several of the QA concerns related to highway structures are shared by that industry. However, in general, the building industry is based on private funding and, in most cases, there is no third-party (e.g., state) review of the design or construction process. Accordingly, the dynamics and relationships of QA components differ. One QA issue that is being reviewed with respect to buildings is traceability. Although not required by the design specifications that govern steel buildings, the issue does elicit attention from the AISC, as noted on its website (www.aisc.org/faq.html). Issues such as lot traceability, piece traceability, main-material versus all-material traceability, consumables (e.g., welding electrodes and paint) traceability, and required record attention are considered by many designers in the building industry.

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