Improving the Quality and Durability of Modular Bridge Expansion Joints

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The Washington State Department of Transportation (WSDOT) has taken steps to improve the quality and durability of modular bridge expansion joints that have a movement rating greater than 150 mm. Expansion joints are subject to a greater number of load cycles than normal bridge components. As a result of premature fatigue failures of modular bridge expansion joints in Washington State and elsewhere, WSDOT requires that all modular joint components meet fatigue design and testing requirements. Components are designed for a fatigue life of 100 million cycles. Fatigue design and testing requirements are included in the contract specifications. Improved specifications and quality control during manufacture and construction are needed in order to eliminate possible loss of quality caused by competitive bidding and bid shopping. Preapproved expansion joint models and manufacturers should be identified in the contract plans and specifications. Contractors should identify which manufacturer is selected at the time of bid submission. It is recommended that modular bridge expansion joints have at least a 5-year guarantee on performance and durability.

The three functional areas concerning bridges are: design, construction, and maintenance. As shown in Figure 1, effective lines of communication between these three areas are critical to ensure that a bridge project is successfully constructed and that existing bridges are safe. The ultimate goal is an aesthetically pleasing bridge with a long service life.

Modular bridge expansion joints are lightweight steel structural systems that permit both translation and rotation between adjacent superstructure bridge elements. The joints are located in the plane of the bridge deck and are perpendicular to the direction of traffic. The movement ratings of modular bridge expansion joints range from 150 to 1280 mm. These watertight joints were developed in Europe in the 1960s and have been manufactured in the United States for more than 20 years.

Two design concepts are used for modular bridge expansion joints: the multiple support bar system and the single support bar system. The multiple support bar expansion joint shown in Figure 2 was first introduced in the United States in the early 1970s. Each steel center beam, which has a sealing element between parallel center beams, is rigidly connected to and supported below by a steel support bar. A horizontal force acting at the roadway surface produces an overturning moment that is resisted by the support bar's span. The horizontal force is transmitted to the bridge by horizontal control springs. The largest multiple support bar expansion joint in Washington State was installed on the Pasco-Kennewick Intercity Bridge in 1978. The 10-seal joint has a total movement capability of 600 mm (*1*).

Figures 3 and 4 show the single support bar concept, which is more complicated than the multiple support bar system. The center beam has a steel yoke that accommodates the support bar. All center beams are supported by the same support bar. Precompressed springs and bearings trap the support bar between the bottom of the center beam and the yoke. The softer spring is below the support bar, and the stiffer bearing is between the center beam and the top of the support bar. The spring/bearing system must allow the center beams to translate along the length of the support bar to accommodate movement. The springs and bearings must also resist overturning while allowing sliding to occur. The two 1280-mm movement joints on the third Lake Washington floating bridge between Seattle and Mercer Island on Interstate 90 are the largest single support bar modular expansion joints in the United States (*2*).

In 1991, as a result of several premature fatigue failures of expansion joint components, the Washington State Department of Transportation (WSDOT) took steps to improve the quality and durability of modular bridge expansion joints. The steps involved fatigue design and testing, stricter quality-control requirements during manufacturing and construction, preapproval based on proven field experience, and a 5-year guarantee of satisfactory performance and durability.

This paper provides background information on fatigue design and testing of modular bridge expansion joints so that effective policy decisions can be made concerning improvements in the quality and durability of these systems.

FATIGUE DESIGN AND TESTING

Static Wheel Load Analysis

In the United States, expansion joints have been designed in accordance with the AASHTO *Standard Specifications for Highway Bridges* (*3*) using AASHTO HS20 wheel loads with an impact factor of 30 percent. Impact factors as high as 60 to 100 percent have been used, depending on local agency requirements. For a 30 percent impact factor, the wheel load is 92.5 kN, and for a 100 percent impact factor it is 142.3 kN. Until recently, the center beam has been analyzed for only static vertical loads either as a beam on rigid supports or as a beam supported by springs. For expansion joints on a 5 to 6 percent grade, an analysis based only on vertical loads may not reflect the actual loading if the effects of horizontal loads are not included. The wheel load distribution to each center

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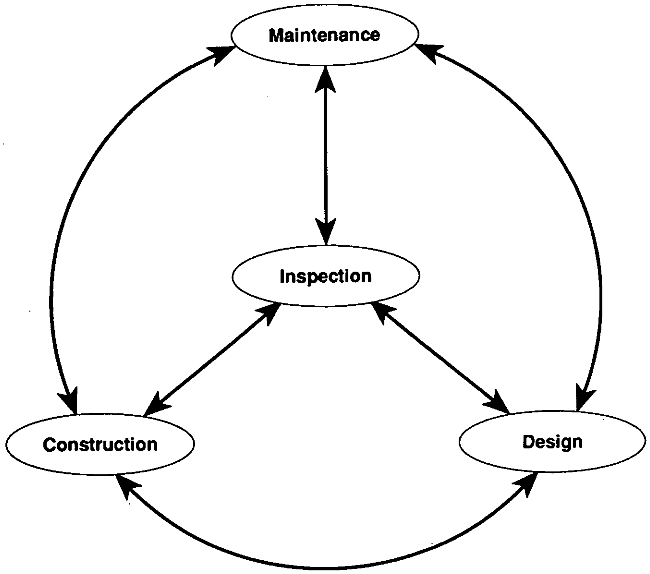

FIGURE 1 Lines of communication between functional areas.

beam depends on the gap between the center beams and the width of the center beam in contact with the tire (*4*).

Fatigue failures in Washington State and on the Burlington Bay Skyway on Queen Elizabeth Way, Ontario, Canada, have occurred after a very short service life: within the first 5 years (*5*). Three failures involved welded connection details. The stainless steel pin failure that occurred at the interface between a center beam and support bar may have been initiated by a crack caused by contact with a snowplow blade. However, "beach marks" on the fractured surface clearly indicate a progressive fatigue failure. It is apparent that a static analysis using allowable service load stresses is not adequate to ensure a long service life. The problem cannot be solved by arbitrarily specifying greater wheel loads or higher impact factors without considering the cumulative damage effects caused by fatigue.

Wheel Load Range for Fatigue Design

Wheel load ranges and allowable fatigue stress ranges for the design of expansion joint components subject to high cyclic loading are not available in the AASHTO *Standard Specifications for Highway Bridges* (*3*). Designers must either extrapolate existing data, which may not be based on adequate testing, or look elsewhere for guidance.

Research in Austria by Tschemmernegg indicates that the fatigue critical details, particularly connections, should be designed for a vertical limit states fatigue load range of 118.3 kN per wheel (+91.0 to −27.3 kN) and a horizontal load range of 36.4 kN/wheel (+18.2 to −18.2 kN) (*4*). These loads include a 40 percent impact factor and are shown in Figure 5; actual measured wheel loads are less than these loads. This vertical load range is very close to an HS25 wheel load plus 30 percent impact, which is 115.6 kN. An HS25 wheel load is 25 percent greater than an HS20 wheel load. The horizontal load range proposed by Tschemmernegg is approximately 30 percent of the vertical load range for an HS25 wheel load with a 30 percent impact factor (*4*).

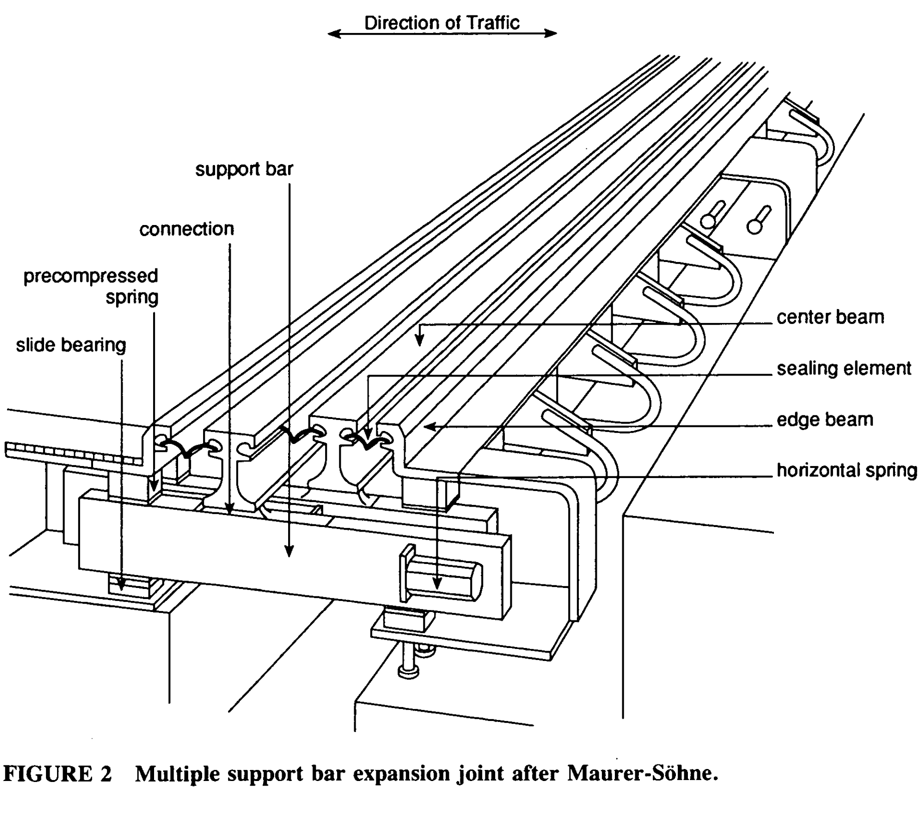

FIGURE 2 Multiple support bar expansion joint after Maurer-Söhne.

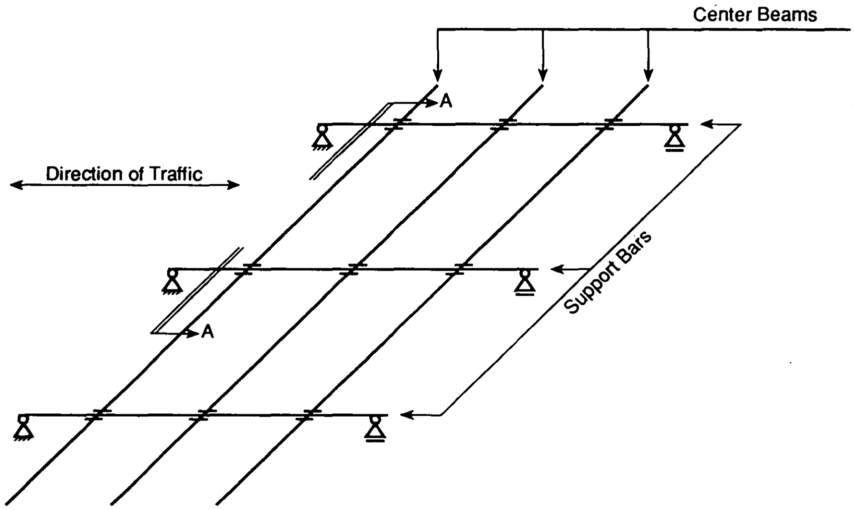

FIGURE 3 Plan, single support bar expansion joint.

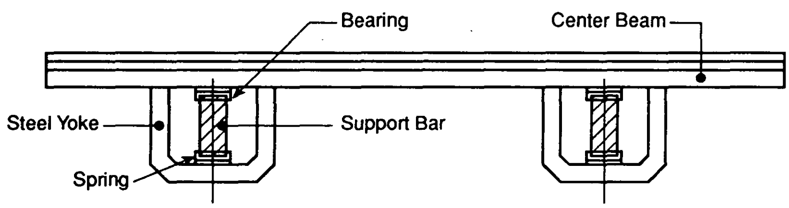

FIGURE 4 Section A-A showing center beam, support bar, springs, and bearings of single support bar system.

The effect of both vertical and horizontal loads on the expansion joint is a function of approach road surface roughness, vehicle speed, dynamic characteristics of both vehicle and expansion joint, and expansion joint vertical and horizontal stiffness. The horizontal loads are associated with the tire rolling resistance, air pressure acting on the vehicle, and tractive or braking forces.

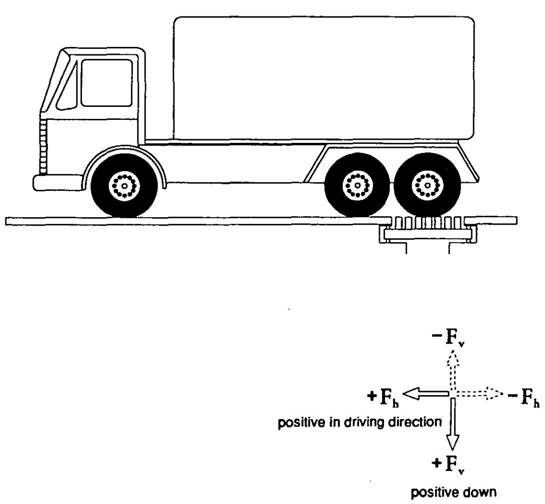

FIGURE 5 Limit states fatigue wheel loads proposed by Tschemmernegg (*4,9*).

Effect of Roadway Grade

The loads shown in Figure 5 are for an expansion joint on a flat or 0 percent grade. As the grade steepens, the horizontal loads parallel to the roadway surface increase by the component of the gravity acting wheel loads (Figure 6). This additional force component of the vertical wheel load is often overlooked by designers. It can be critical since horizontal forces produce a torque on the center beam and an increase in the stresses in the fatigue-sensitive connection between the center beam and support bar. The load ranges of fatigue limit states should be modified to account for the increased horizontal force caused by roadway grade.

Effect of Support Settlement

Settlement of the center beam is caused by deflection of the support bar, softening or creep of the support bar bearings, or potential foundation settlement in the anchorage area. In the more-complicated single support bar system, the potential for settlement is greater because there are additional springs and bearings at the intersection of the center beam and support bar. If these springs and bearings creep over time, the center beam can deflect under wheel impact loads.

Any support bar settlement caused by softening of the bearings or gaps caused by complete loss of precompression, including those at the ends of the support bar, will produce

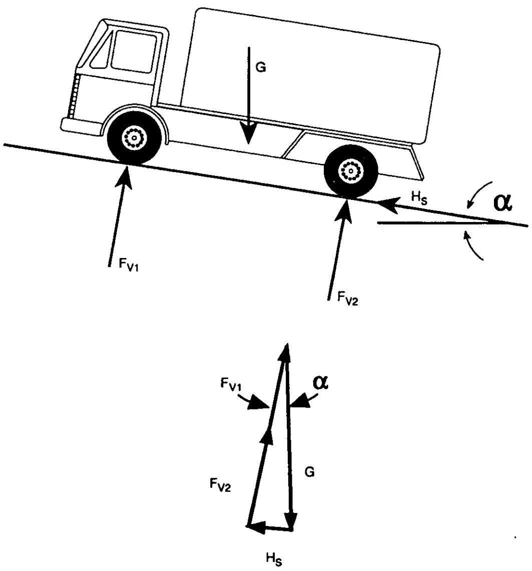

FIGURE 6 Effect of roadway grade (*top*) and horizontal force (H_S) on rear drive wheels due to grade (*bottom*).

additional stresses in the center beams. Settlement of supports may produce a greater fatigue stress range than initially assumed in the original design because the effective span has increased.

Fatigue Limit States Design

Limit states design has been widely used in Europe and Canada (*4,6*). In the 1980s, it gained acceptance in the United States for steel building design. Known as load and resistance factor design (LRFD) (*7*), this probabilistic design method was developed by Galambos and Ravindra at Washington University in St. Louis, Missouri (*8*).

For expansion joint design, no LRFD criteria, calibration, or evaluation studies have been done in the United States. However, as a result of long-range fatigue testing of expansion joint details, Tschemmernegg at the University of Innsbruck has developed a limit states fatigue procedure applicable to expansion joint design (*4*).

One of the design limit states is the serviceability of the expansion joint; specifically, the expansion joint components are to remain free of cracks after 100 million cycles, which is assumed by Tschemmernegg to be an infinite life. Since expansion joints are subject to a greater number of load cycles and higher impact than other bridge components, fatigue testing of critical components and connections is necessary to establish the theoretical limiting stress range at the endurance limit of 100 million cycles. The fatigue limit states equation proposed by Tschemmernegg (*4;9*,p.2) is

$$(0.5)f_{sr\ calc} \leq F_{sr\ test} \qquad (1)$$

where $f_{sr\ calc}$ is calculated stress range based on fatigue wheel load range and $F_{sr\ test}$ is theoretical fatigue stress range at 100 million cycles determined from S-N tests.

Fatigue Testing and Development of S-N Diagrams for Critical Details

The phenomena of fatigue failure and fatigue cracking of steel bridge structures have been described by Fisher et al. (*10*,p.26;*11*,p.252). Plots of stress range versus number of cycles, or S-N diagrams, are developed from constant amplitude fatigue tests for critical details. Typical S-N diagrams for AASHTO Categories A to E′ are shown plotted in Figure 7. For ferrous metals, these diagrams are generally straight lines with a slope of approximately 3 to 1 (horizontal to vertical) on a log-log plot.

Bridge structure components are subject to loads that produce variable amplitude stress ranges. However, research has shown that if a structure is to remain free of cracks, the maximum stress range it experiences due to live loads must be less than that obtained from a constant amplitude S-N diagram for a specific number of cycles. If any stress range cycles, including those produced by overloads, exceed the allowable fatigue stress ranges determined from a constant amplitude fatigue test, fatigue cracking is likely (*10*,p.26).

Each fatigue critical detail has a characteristic fatigue strength that is a function of loading range, number of cycles of loading, geometry, type of connection, inherent stress risers, and material properties. Figure 8 shows a welded center beam–to–support bar connection tested by Tschemmernegg (*4*). The proposed S-N diagram for this detail (Figure 9) shows that the slope from N = 100,000 cycles to N = 5 million cycles is 3 to 1 (m = 3). From N = 5 million to N = 100 million cycles, the slope is 5 to 1 (m = 5), and for more than 100 million cycles, the slope of the S-N curve is 0 (m = 0). The stress range at 100 million cycles is the theoretical endurance limit.

Figure 9 is constructed from constant amplitude fatigue testing of a number of test specimens at different stress ranges to determine the number of cycles to produce fatigue cracks. Generally, three specimens are tested and at least one specimen exceeds 2 million cycles without cracking. On the basis of a probability analysis, a stress range with a 95 percent confidence level is established at 2 million cycles (Point C, Figure 9). The proposed S-N diagram is drawn through the 95 percent confidence point. The theoretical endurance limit at 100 million cycles is established from the known slopes of the S-N diagram using the appropriate logarithmic relationships.

It is possible to satisfy the AASHTO fatigue design stress range for more than 2 million cycles while not satisfying the fatigue design stress range at 100 million cycles proposed by Tschemmernegg (*4*). Therefore, it is important that fatigue critical details be tested to establish S-N diagrams and to determine the theoretical endurance limit at 100 million cycles.

QUALITY AND DURABILITY

M. P. Burke recently noted the effects of the current competitive bidding practice on the quality and durability of bridge deck joints and bearings when specifications are incomplete:

> As competition between products drives prices down, manufacturers are forced to reduce the prices of their products to remain

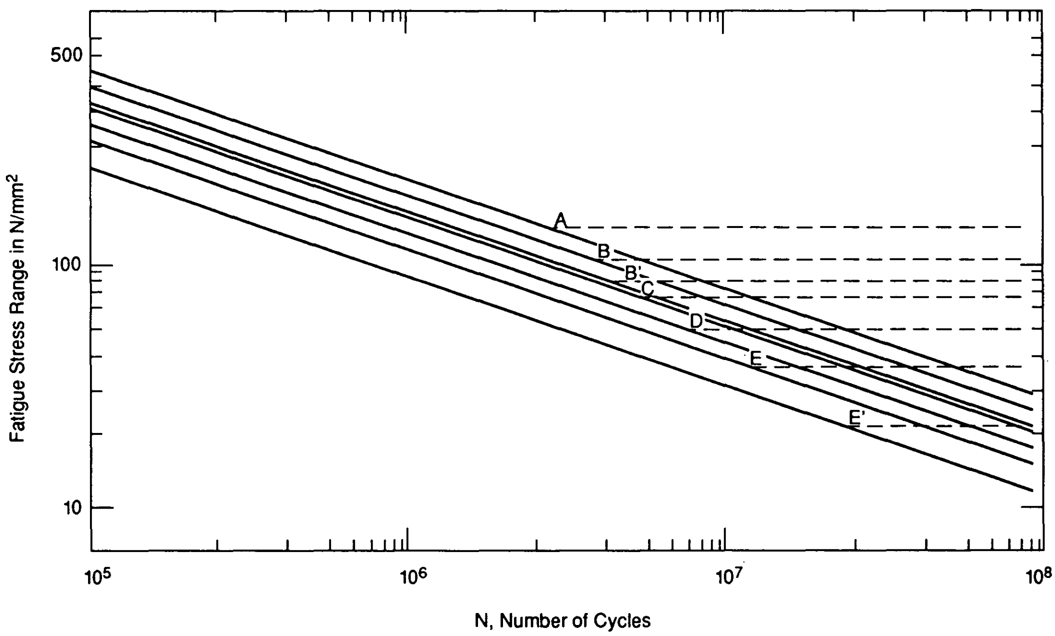

FIGURE 7 Design fatigue stress range curves for AASHTO Categories A to E′ (*11*).

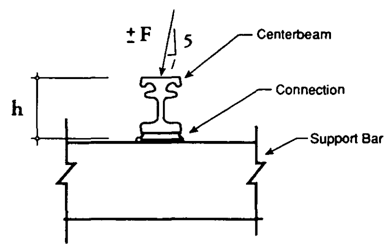

FIGURE 8 Fatigue testing of connection by Tschemmernegg (*4,9*).

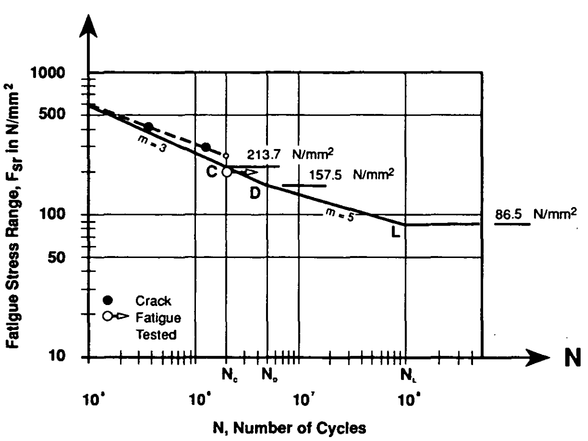

FIGURE 9 S-N diagram for connection proposed by Tschemmernegg (*4,9*).

competitive. And since the quality has not been described and quantified (measured), the design of products and their quality can be changed, lowered in most cases, to make them more competitive. Ultimately, the quality available in such devices will adversely affect their integrity and durability and consequently their suitability for particular applications. (*12*)

Competitive bidding, bid shopping (*13*), and value incentive clauses in contract specifications should not pose problems for owners if the contract specifications are complete. These documents should clearly specify the requirements and how compliance with these requirements is to be determined and enforced. Specifications should include acceptable manufacturers, design loads, design parameters, required testing, approved testing facilities, material specifications, testing requirements, quality-assurance requirements, guarantee, and certificates of compliance. Specifications should require that the manufacturer be identified at the time bids are submitted. In the contract bid documents, the pay item for expansion joints can be separated into two parts: supplying and installing the expansion joint.

The following topics describe criteria in WSDOT contract specifications to ensure that quality is addressed in expansion joint design, manufacture, and installation.

Quality Control During Design

Calculations for structural components are stamped by the engineer in responsible charge of the design. The engineer must be a full-time employee of the expansion joint manufacturer and a registered professional engineer. The design calculations shall include a fatigue analysis supported by test data. Fatigue testing is done at test sites approved by WSDOT, not at the manufacturer's plant. Joints that have proven field experience are specified and are identified by model and manufacturer. Other design, specification, and shop plan review criteria for joints used by WSDOT have been described previously (*14*).

Required Certificates

Besides the submission of design calculations with the shop plans and welding procedures, certificates of compliance, test reports, and material samples are submitted for review, testing, and approval.

Some required certificates of compliance are

- Manufacturer's certificate of compliance with the American Institute of Steel Construction Quality Certification Program, Category III, Major Steel Bridges.
- Certification of welding inspectors under American Welding Society QC1, Standard for Qualification and Certification of Welding Inspectors.
- Certification of personnel as NDT Level II nondestructive testing inspectors under the American Society for Nondestructive Testing Recommended Practice SNT-TC-1a.
- Certified mill test reports for all steel and stainless steel in the expansion joints and other material certificates.
- Certified test reports confirming that the springs and bearings meet the design load requirements.

Inspection Requirements

Three levels of inspection must be satisfied before the expansion joints are accepted: quality-control inspection, quality-assurance inspection, and final inspection. The manufacturer provides for both quality-control and quality-assurance inspection. If the expansion joints fail any one of the three levels of inspection, they are replaced or repaired. Any proposed corrective procedure is submitted for WSDOT's approval before the corrective work is begun.

Quality-Control Inspection

During the fabrication process, the manufacturer provides full-time quality-control inspection to ensure that the materials and workmanship meet or exceed the minimum requirements of the contract. Quality-control inspection is the responsibility of the manufacturer's quality-control department.

Quality-Assurance Inspection

Quality-assurance inspection is performed by an independent inspection agency provided by the manufacturer and approved by WSDOT before fabrication is started. Quality-assurance inspection is not required to be full-time inspection but is done at all critical phases of the manufacturing process before and during assembly of the expansion joints.

Final Inspection

Upon arrival at the job site and before installation, the expansion joints are inspected by WSDOT personnel. A clean, dry, enclosed area is provided by the contractor for the final inspection.

Quality Assurance During Construction

Proper installation of the expansion joint during construction is critical to ensure a long service life. Expansion joints are one of the last items to be installed during bridge construction. WSDOT has taken the following steps to ensure adequate quality control during installation:

1. A qualified installation technician, who is employed full-time by the joint manufacturer, is on site to ensure that each expansion joint is installed properly.
2. The contractor shall adhere to recommendations made by the installation technician and approved by WSDOT's field engineer.
3. The contractor shall at all times protect the expansion joints from damage.
4. Before installation of the joint, the blockout and supporting system are protected from damage and construction traffic.
5. After installation, construction loads are not permitted on the joint. The contractor is required to bridge over the joint.
6. All forms and debris that tend to interfere with the free action of the joint are removed.
7. The expansion joint is water-tested after installation to ensure that it is watertight.
8. Upon completion of the water test, the joint manufacturer's installation technician certifies in writing that the contractor followed the proper installation procedure.

Partnering

In any undertaking, quality and durability are attainable only if all parties involved—contractor, owner, and joint manufacturer—are working as partners or team members with common goals. WSDOT uses partnering to enhance a cooperative climate with the contractor and to manage conflict on the construction project (*15*,p.14).

Guarantee

WSDOT has required a 5-year guarantee for two large-movement expansion joints to ensure satisfactory performance and durability. The following guarantee was used on a recent WSDOT contract for a large-movement expansion joint with a 900-mm movement range:

> The Contractor shall provide a five-year written guarantee for the operation and durability of the expansion joints. Broken welds or bolts, cracks in steel members, fatigue, loss of precompression in springs or bearings, debonded TFE, breakdown of corrosion protection, and leakage shall constitute unsatisfac-

tory operation and durability of the joints. Replacement or repair of any joint parts within the first five years, commencing from the date of completion of the contract, shall be covered under the guarantee. The Contractor shall replace or repair any joint parts within the period of the guarantee at the Contractor's expense.

If problems occur with expansion joints, they will most likely occur within the first 5 years of service. Guarantees for manufactured items should be mandatory on all projects. Federal regulations that prohibit the use of federal funds from being used on a project if guarantees are specified should be revised. Guarantees for manufactured items provide a measure of security for owners.

ACCESSIBILITY AND MAINTAINABILITY

In 1990–1991, FHWA conducted a field evaluation on the performance of large-movement finger and modular expansion joints in six states: Florida, Kansas, Michigan, New York, Washington, and Wisconsin. Romack noted that limited-access space made inspection and repair of modular bridge expansion joints difficult for maintenance personnel (*16*). The complexity of these systems demands expertise and equipment that is beyond the capability of the average bridge maintenance crew. Training and technical assistance is required before undertaking repairs. Traffic control, lane closures, and the need to work at night make the repair of these systems expensive.

Bridge designers and expansion joint manufacturers must address the need for maintenance. Expansion joints are not maintenance-free. As with any mechanical system, replacement of parts subject to wear must be allowed for in the design (*17*). The manufacturer should make recommendations as to how often parts should be inspected. Wear tolerances and methods for determining wear should be made part of the maintenance and part replacement plan.

CONCLUSIONS

1. Background information on the fatigue design of modular expansion joints is given.
2. Design based on a static analysis and allowable service load stresses is inadequate to ensure a long service life for expansion joint components subjected to high cyclic loading.
3. Designers and joint manufacturers need to provide additional access space for inspection, maintenance, and repair of expansion joints.
4. Teamwork between contractor, owner, and joint manufacturer is essential to ensure a successful expansion joint installation.
5. Repair and replacement of failed expansion joint components is expensive and time-consuming.

RECOMMENDATIONS

1. Fatigue design and testing should be required for all modular bridge expansion joints. A minimum of 100 million cycles should be used to determine the theoretical endurance limit of fatigue critical details.
2. AASHTO specifications should include fatigue design and fatigue testing requirements and procedures for expansion joint components.
3. Specifications should include quality-control and inspection requirements during manufacture and installation to ensure durability and a long service life.
4. Specifications should be written in clear, specific language.
5. Preapproved expansion joint models and manufacturers should be identified in the contract plans and specifications. Contractors should identify at the time of bid submission which manufacturer is selected.
6. A written maintenance and part replacement plan should be included at the shop plan submission stage. A list of parts to be inspected, acceptable wear tolerances, and method of part replacement should be included.
7. A minimum 5-year guarantee on performance and durability should be required. Federal regulations prohibiting the use of guarantees should be revised.

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