GUIDELINES FOR MAINTAINING SMALL MOVEMENT BRIDGE EXPANSION JOINTS

FINAL REPORT (PART 1)

Prepared for
NCHRP
Transportation Research Board
of
The National Academies

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September, 2016

ACKNOWLEDGMENT

This work was sponsored by the American Association of State Highway and Transportation Officials, in cooperation with the Federal Highway Administration, and was conducted in the National Cooperative Highway Research Program, which is administered by the Transportation Research Board of the National Academies.

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Author Acknowledgments

The research reported herein was performed under NCHRP project 12-100 by the Department of Civil and Environmental Engineering of the University of Delaware (UD), and Greenman-Pederson Inc (GPI), of Albany, New York. The University of Delaware was the prime contractor for this study.

Dr. Harry “Tripp” Shenton, Ph.D., Professor and Chair of Civil and Environmental Engineering at UD was the Project Director and Principal Investigator. The other authors and Co-Principal Investigators of the project are Dr. Dennis R. Mertz (deceased), Professor of Civil Engineering at UD, and Mr. Peter J. Weykamp, P.E., of GPI. Also contributing were Mr. Matt Sparacino, graduate research assistant in civil and environmental engineering at UD.

The research team would like to thank the many bridge owners, consultants, contractors, and vendors and suppliers of bridge joints for their valuable input and feedback on the project. The team would also like to thank the NCHRP panel for their contributions. Finally, the team would like to thank Mr. Gary Wenczel, laboratory manager at UD , for his support in conducting the tests of foam materials.

Abstract

This report documents and presents the results of a project aimed at developing guidelines for maintenance and repair of Small Movement bridge Expansion Joints (SMEJ): small movements are defined as 4 inches or less. The key tasks in the project were a literature survey, survey of key stakeholder groups, development of procedures for replacing, repairing, and maintaining SMEJ's, and finally, developing draft guidelines that would be suitable for AASHTO. The literature survey and stakeholder survey provided valuable information on the prior work conducted and current state of practice with regard to SMEJ's. The research examined best practices through interviews and data gathering from owners and suppliers, performance metrics, life-cycle cost analysis, common material tests of joints, and compression set in closed-cell foam. Detailed procedures were developed that address types of SMEJ's, modes of failure, evaluating joints, calculating joint movement and sizing the seal, selecting a replacement joint, procedures for repair and replacement of the header, and procedures for replacement, repair, and maintenance of the main types of SMEJ's on the market at the time of writing. These procedures formed the basis for the proposed Guidelines that were developed as a standalone document that is suitable for adoption by AASHTO.

Summary

Guidelines for replacing, repairing, and maintaining Small Movement bridge Expansion Joints (SMEJ) were developed (small movement is defined as 4 inches or less). A literature survey was conducted that showed a dearth of work on SMEJ's. A stakeholder survey was conducted of bridge owners, contractors, consultants, and suppliers that provided a good picture of the current state of practice with regard to SMEJ's. Using this as a foundation, a variety of tasks were conducted in support of developing detailed procedures for replacing, repairing, and maintaining SMEJ's. These procedures became the basis for the proposed guidelines, which were developed as a standalone document suitable for AASHTO consideration.

The proposed guidelines cover the key types of SMEJ's in use today: asphalt plug joint, compression and bonded joints, strip seal joints, pourable joints, and open joints. Typical schematics and photographs of these joints are presented, as are their typical modes of failure. A procedure for evaluating joints is proposed that is based on the AASHTO Manual for Bridge Element Inspection condition states and defect definitions, to determine when a joint should be maintained, repaired, or replaced. Details on how to calculate joint movement and size a seal are presented. This section also explains how to calculate maximum expected compression, tension, shear, and compression at install, based on the gap width and temperature when the seal is installed. Next the guidelines discuss selecting a replacement joint. This is based on key performance metrics for a joint: joint opening, joint movement, skew, expected service life, installed cost, constructability, lead time, location, traffic, and durability. A table is presented that shows typical values for each of these metrics for the key types of SMEJ's: some metrics are quantitative and others are qualitative. Factors to consider when switching from one joint type to another are presented. Detailed procedures are then presented for replacing and repairing the header. This is then followed by detailed procedures for replacing, repairing, and maintaining each of the five main categories of SMEJ's. A separate section for each type of joint is presented that provides detailed step-by-step procedures for each of these activities. The sections end with a collection of photographs that show the steps involved in replacing the joint.

It is hoped that with the adoption of these proposed guidelines, owners can begin to see longer life joints and reduced costs associated with deteriorated joints.

1. Introduction

Scope and Objectives of the Project

The University of Delaware (UD) with Greeman-Pedersen, Inc. (GPI), was contracted by the National Academy of Sciences (NAS) to carry out the work for project NCHRP 12-100 "Guidelines for Maintaining Small Movement Bridge Expansion Joints." The objectives for the project were to develop proposed guidelines with commentary for evaluating and maintaining small movement bridge joints to support the decisions of bridge owners. The guidelines would cover, as a minimum: (1) joint failure mechanisms; (2) performance metrics and (3) procedures for maintenance, repair, and replacement of bridge joints. The proposed guidelines are to be presented in a format suitable for AASHTO consideration.

The project was broken down into two phases, with a total of 8 tasks. Phase I focused on "Synthesis Report and Procedures Development," and included the tasks:

Task 1: Literature survey/review
Task 2: Survey of stakeholders
Task 3: Technical memorandum summarizing Tasks 1 and 2
Task 4: Develop procedures for maintenance, repair, and replacement of joints
Task 5: Prepare an outline of the proposed guidelines
Task 6: Interim report

Phase II focused on "Guidelines Development," and included the tasks:

Task 7: Develop proposed guidelines
Task 8: Prepare final deliverables

The scope of the work was limited to "small movement" bridge expansion joints, which were defined in the project RFP to be joints with movements less than or equal to 4 in. In the early phase of the project the research team adopted the following definitions for maintenance, repair, and replacement:

Maintenance – any activity that is done on a regularly scheduled, cyclic basis (e.g., every year, every two years) to maintain the proper operation of the joint.
Repair – any activity that is done on an intermittent basis to bring a joint back to proper functioning; may involve work on a portion of the joint, or the entire joint, but does not constitute a complete reconstruction of the entire joint.
Replacement – a complete reconstruction of the entire joint.

These have been used throughout the project and in the guidelines to differentiate these activities, as they relate to small movement bridge expansion joints.

Definitions

To begin, it is helpful to define a number of terms that are commonly used herein.

Joint movement – the opening or closing displacement of the joint caused by the change in temperature of the bridge.

Joint gap – the nominal opening of the joint that must be spanned; is set at the time of construction or reconstruction of the joint.

Seal – the flexible material that spans the joint opening; sometimes also referred to as a gland, gasket, or membrane.

Blockout – the sections at the end of bridge spans and abutment back walls formed to anchor the joint system.

Header – the material placed in the blockout.

Types of Joints

Presented here are the most common types of small movement bridge expansion joints in use today.

Asphalt Plug Joint (APJ)

The APJ consists of a flexible asphaltic material placed over a steel plate that bridges the joint gap. A foam backer rod is placed in the joint gap; steel locating pins (centering pins) placed through the plate and into the backer rod keep the bridging plate centered over the gap. APJ's are usually limited to joint movements up to 1 in. and are typically used with asphalt overlays. A schematic and photograph of an APJ is shown in Figure 1.

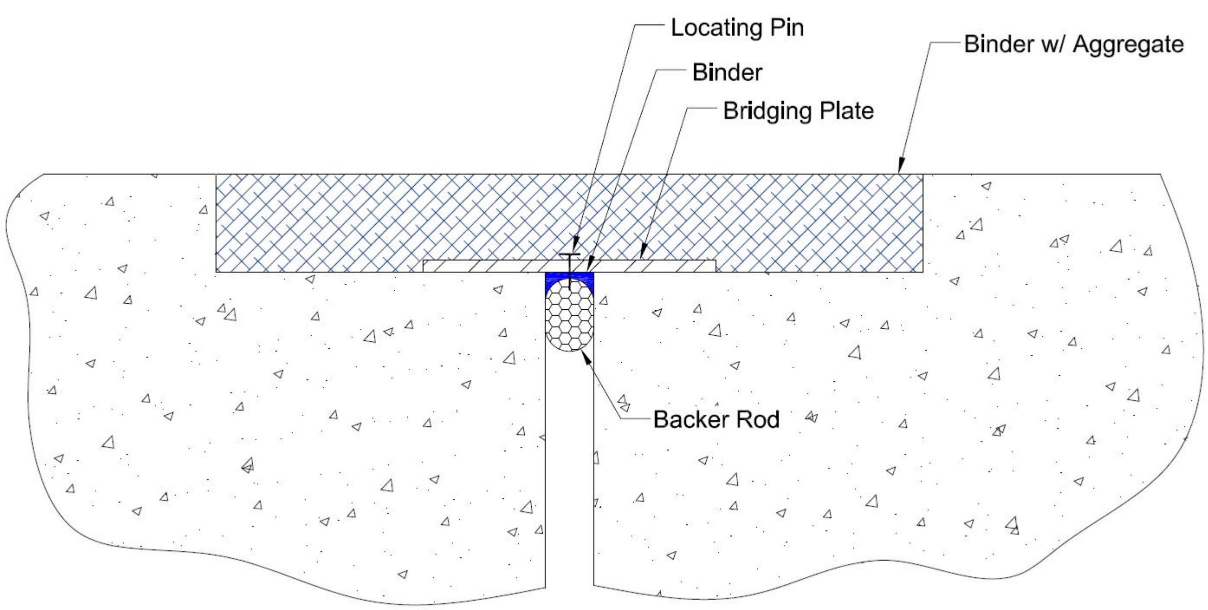


FIGURE 1.

Figure 1 Schematic and photograph of a typical Asphalt Plug Joint

Compression and bonded seal joints

As the name implies, the compression seal relies on compression to keep the joint seal in place and the joint watertight. Compression seals are defined as preformed polychloroprene elastomeric joint seals per ASTM D3542 description as well as AASHTO M297-10. An elastomeric seal that has a webbed cross-section (Figure 2) is a compression seal. As defined by ASTM “the seal consists of a multiple web design and functions only by compression of the seal between the faces of the joint with the seal folding inward at the top to facilitate compression".

It is generally recommended that compression seals are set onto supports, either metal “keeper bars” welded onto an armoring plate or by saw cutting the opening slightly wider on both sides to the required depth thereby allowing the seal to be seated. A lubricant/adhesive that acts as both an adhesive and lubricant is used in the installation of compression seals. Compression seal movements do not exceed 2 1/2".

Bonded joint seals are bridge seals that work in both compression and tension. Open and closed-cell foams, and preformed “ʌ” or “M” forms are bonded seals. These seals can expand beyond their nominal width. Bonded joint seals are installed using a 2-part epoxy. These seals can typically accommodate movements up to 3 to 4 inches, depending on the type. Schematics of bonded seal joints are shown in Figure 3 through Figure 5.

The manufacturer will specify a minimum and maximum joint opening along with minimum installation widths for both compression and bonded seals. In addition, a depth should be listed for proper setting of bonded and compression seals.

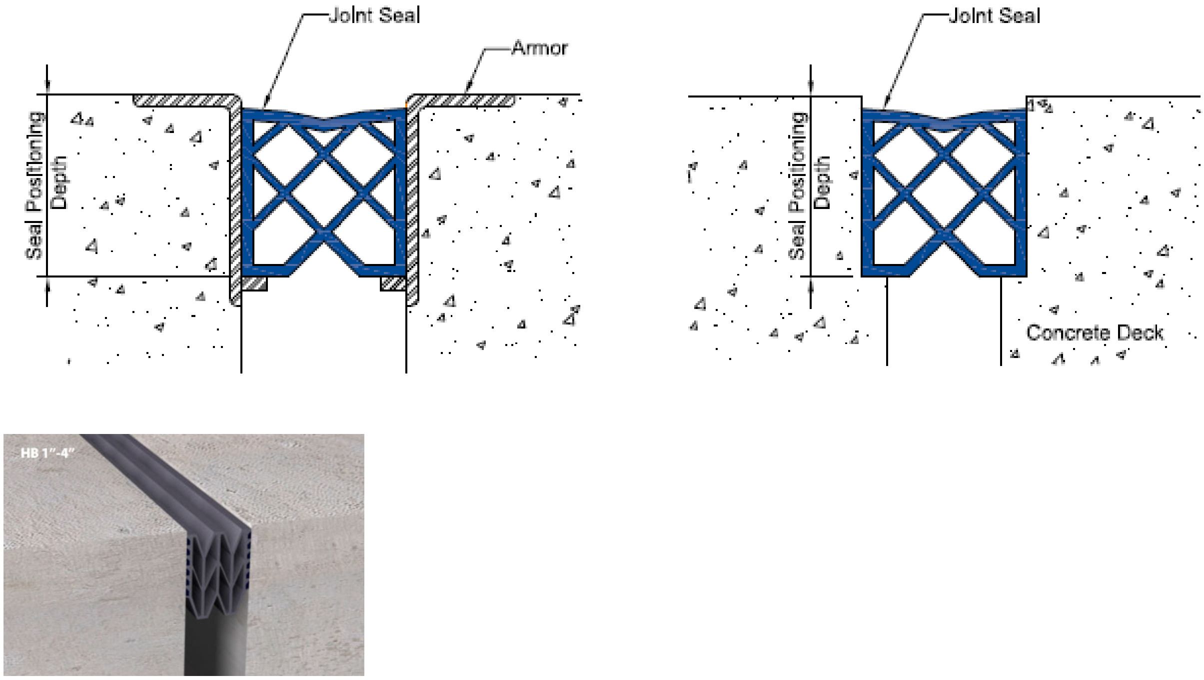


Figure 2 Elastomeric cellular type compression seal shown with and without optional armor angle

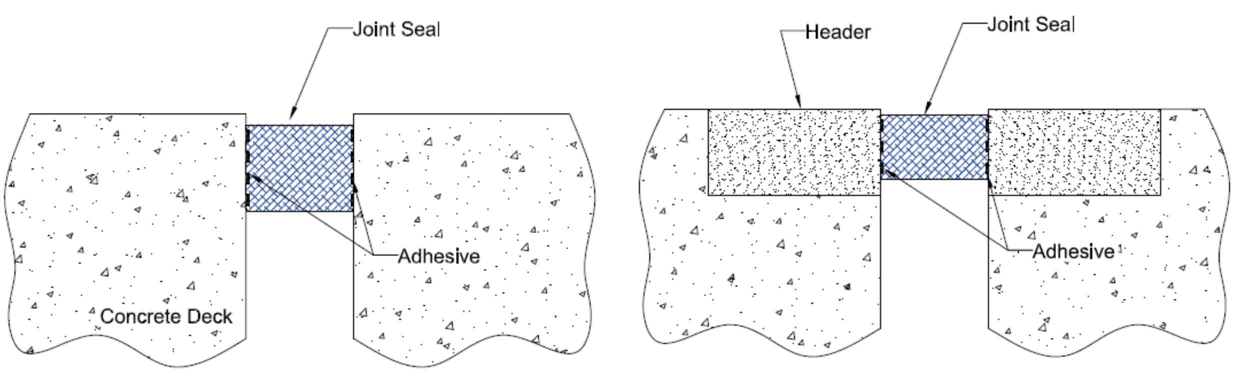


Figure 3 Closed-cell foam type bonded seal

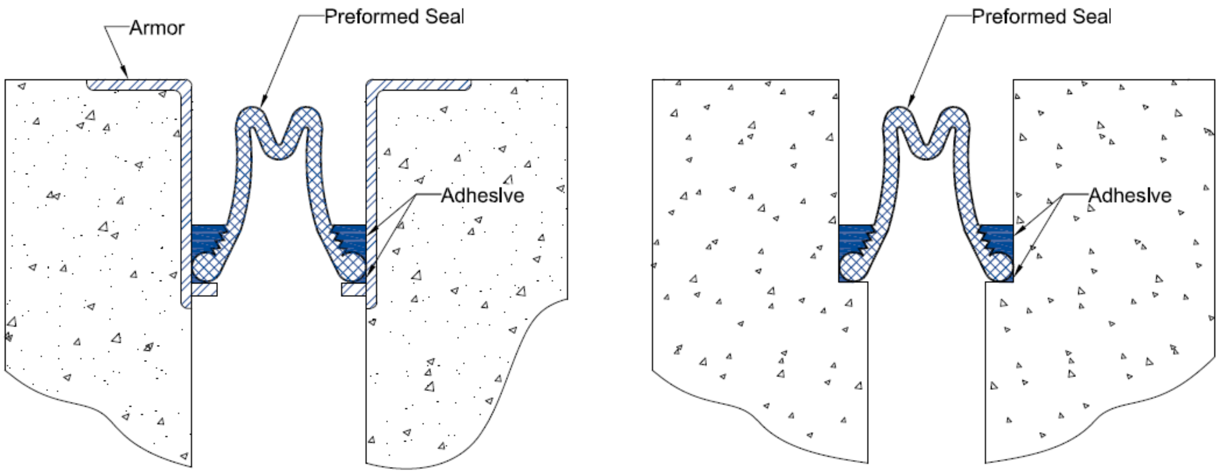


Figure 4 Preformed bonded "M" type seal

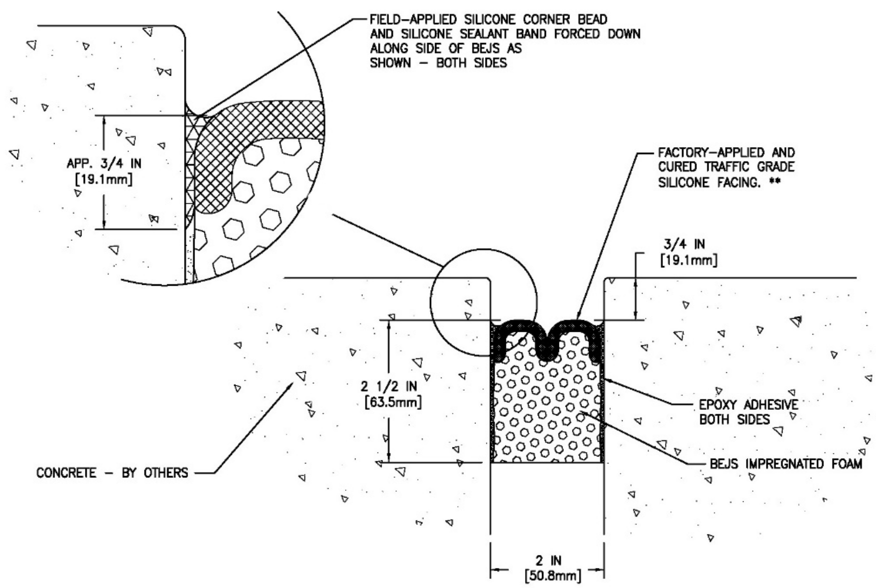
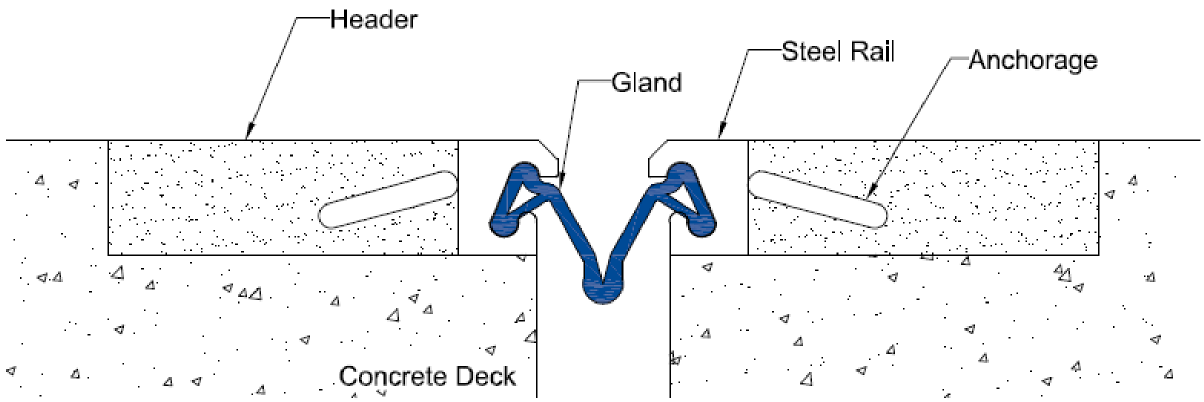


Figure 5 Precompressed, self-expanding open cell foam bonded joint seal

Strip seal/armored joint

A strip seal consists of an elastomeric seal anchored to a steel rail embedded in the header. A schematic of a strip seal is shown in Figure 6. This type of joint can typically accommodate joint movements up to 3 to 4 inches perpendicular to the joint. The seal and rails come in various shapes and sizes.



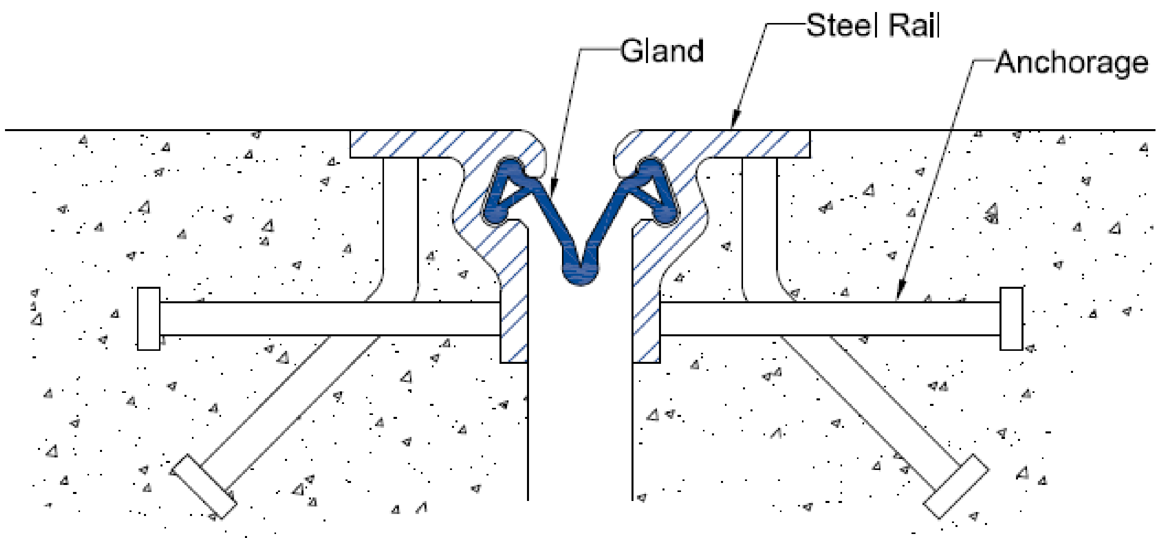
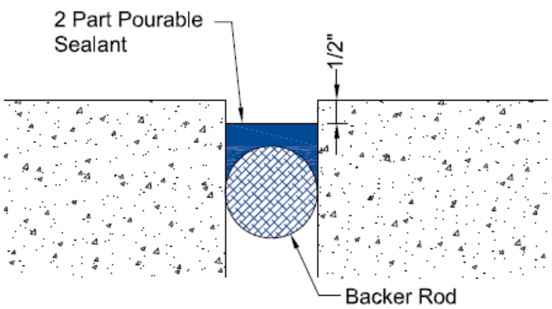


Figure 6 Schematic and photograph of a typical strip seal

Pourable

A pourable seal consists of a backer rod placed in the joint gap, on top of which is placed, i.e., poured, a liquid, self-leveling, quick curing silicone or urethane-based material. Joint movements up to 1 in. can be accommodated. The silicone and urethane products are a 2-part material that are mixed on site. A schematic of a poured seal is shown in Figure 7.



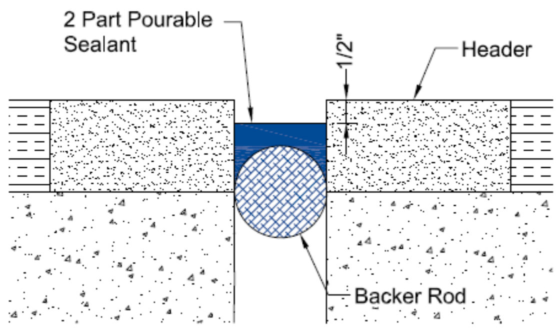


Figure 7 Schematic and photograph of a typical poured seal joint

Open/sliding plate/butt

This type of joint, sometimes just called an “open” joint, is designed to allow water to flow through the joint gap. It can be designed with or without a trough below the joint, which is designed to capture the water and direct it to the side and away from the bridge. The open or butt joint is completely open, i.e., there is nothing in, or bridging the joint gap. The sliding plate joint is an open joint that has a plate that bridges the joint gap. This type of joint can typically accommodate joint movements up to 2 to 3 in. A schematic of the open joint is shown in Figure 8.

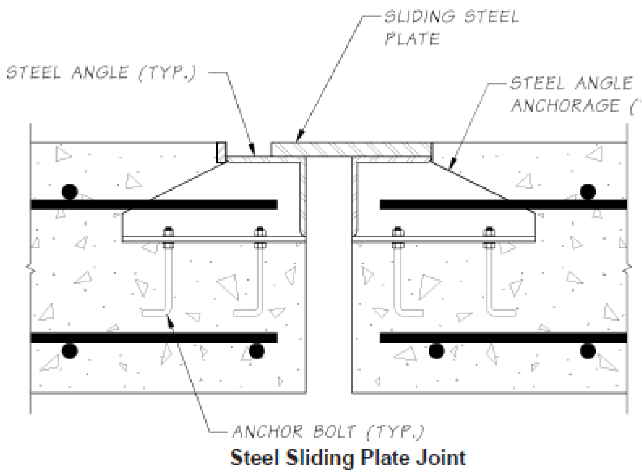


Figure 8 Schematic and photograph of a typical sliding plate joint

Report Organization

This report summarizes the work conducted and the findings of the project. The proposed guidelines for maintaining, repairing, and replacing small movement bridge joints have been developed as a standalone document that can be presented to AASHTO; the guidelines are presented in a separate document called "Guidelines for Maintaining Small Movement Bridge Expansion Joints - Final Report (Part 2)". The results of the research and data gathering, that were carried out primarily in Tasks 1, 2, and 4 of the project, and that provided the foundation for the guidelines, are presented in this report. The results of the literature survey and review that was conducted in Task 1 is presented in Chapter 2. Presented in Chapter 3 are the results of the survey that was conducted of bridge joint stakeholders (owners, contractors, consultants, and suppliers). Chapter 4 presents the results of a variety of topics that were investigated as part of the project to support the development of the guidelines. An outline of the procedures developed under Task 4 of the project that became the basis for the guidelines is presented in Chapter 5. A summary and conclusions are presented in Chapter 6.

2. Literature Review

The objective of Task 1 of the project was to conduct a comprehensive review of literature of the state-of-practice and the state-of-knowledge of small movement expansion joints. Several comprehensive databases were searched for literature that reports on research conducted on Small Movement Expansion Joints (SMEJ). Design manuals and maintenance guides, when available, were collected from state agencies. Below is a summary of the review.

Purvis and Berger (1983) give an overview of the most commonly used joints in the U.S. at the time, including open joints (butt, plate, tooth) and closed joints (filled, compression seal, membrane, cushion (a neoprene reinforced pad anchored on each side of the joint)). There is a brief comment on effective maintenance strategies for each joint. At the end of the article there are suggestions for improving the overall method of joint maintenance, such as creating a system that converts inspection ratings to maintenance priorities to facilitate more realistic budgeting. It also recommends investing more time in addressing inadequacies with timely and appropriate maintenance strategies, and not in modifying the design of these joints to account for very specific problems (which the article claims may never happen).

"The Performance in Service of Bridge Deck Expansion Joints", by A. R. Price (1984), is a Transport and Road Research Laboratory (TRRL) report that investigates the performance of five types of expansion joints used in the U.K. over a seven year testing period. A multitude of each joint was selected from a variety of bridges carrying different types and frequencies of traffic, to ensure an exhaustive evaluation was conducted. Observations of the joint's environment were made including workmanship, installation, weather, traffic, and temperature. Based on visual observations, photographic records, and measured data, an in-depth performance analysis is provided that describes the primary uses and common failure modes of each joint, including a description of factors that influence these failures modes as well as overall performance. Quantitative magnitudes are provided, including typical values for parameters such as joint vibration due to traffic, thermal expansion (relative to design values), etc. The discussion contains many recommendations for an increased service life, specifically referencing improvements to design practices. It points out that a designer must carefully select a joint based on its range of motion, as well as the structural behavior in the vicinity of the joints, the site conditions, and the frequency and nature of the traffic loading. Among the other recommendations for increased service life, greater care during installation is discussed, as many joint deficiencies were suspected to have resulted from improper installation. All of these recommendations are supported by the observation that while the installation of an expansion joint is relatively inexpensive, the repair of an in service joint can become quite expensive and obtrusive to traffic flow. A final result is a table that shows, by joint type, the various factors that affect joint performance and assigns a "High", "Medium," or "Low" designation to each of these depending on how influential the factor is on joint performance.

Dahir and Mellott (1987) reported on a study conducted for the Pennsylvania Department of Transportation, in cooperation with the Federal Highway Administration, to evaluate the performance of in-service joints in Pennsylvania. This work has the most relevance to the current project. In the study all joints currently in use in PA at the time were identified and categorized by range of movement. A

section is provided that outlines the details of every joint in use, and common problems of each. A total of 57 different joint systems were identified on 146 different bridges. Two teams of engineers, working in pairs, were assigned to inspect all of these joints. An evaluation form was provided by FHWA for rating joints on a 0 (failure) to 5 (excellent) scale, on the following joint parameters: A-general appearance, B-condition of anchorage, C-debris accumulation, D-watertightness, E-surface damage, F-noise under traffic, and G-ease of maintenance. The parameters were also weighted by the inspection team members according to their perceived significance to joint performance, as follows: general appearance (9%), condition of anchorage (26%), debris accumulation (9%), watertightness (27%), surface damage (12%), noise under traffic (8%), and ease of maintenance (9%). Each unique joint was inspected and given a 0 to 5 score for each of these factors. The results were then compiled in a table by joint type. An unweighted average score and a weighted average score were then calculated for each joint type. The final table from the study is reproduced in Figure 9. In this table the different types of joints are listed in the left most column; in the second column are the number of joints of that type that were inspected. The integer numbers listed under the columns labeled “A” through “G” are the sum of the 0 to 5 scores given by all four inspectors for those joints. The unweighted average score and the weighted average score are shown in the last two columns of the table.

Based on experience and engineering judgment, the team assigned ranges for the weighted average that defined poor, fair, satisfactory, good, and excellent performance. Poor was anything less than 3.50, fair was 3.5 to 3.84, satisfactory was 3.85 to 4.19, good was 4.2 to 4.59, and excellent was anything greater than 4.60. A final recommendation is made that only joints with ratings equal to or greater than 3.85 should be used, and those that require low maintenance should be used. Additional conclusions include four important questions that designers should consider when selecting a type of expansion joint:

1. “Can the system stand the continuous pounding of traffic, particularly truck traffic, without undergoing surface damage or structural damage in the system? Also, is the system protected against snow plow damage?”
2. “Is the system designed such that water contaminated with deicing chemicals, sand, and other debris will not collect in it long enough to affect its performance adversely?”
3. “How will the system perform when maintenance is neglected for a period exceeding expected maintenance schedules?”
4. “How easily can the system be maintained with minimal traffic delay and without elaborate maintenance procedures?”

TABLE 1 SUMMARY OF RATINGS BY JOINT SYSTEM TYPE

Model Name	Condition No.	A	B	C	D	E	F	G	Unadjusted Avg	Weighted Avg
Compression seals (neoprene)										
Armored (AR)	54	211	208	196	129	201	210	208	3.79	4.15
Preformed (PN)	5	20	20	20	20	20	20	20	4.00	4.00
Strip Seals										
Strip seals (SS)	7	28	28	12	26	28	26	23	3.49	3.63
Harris (HA)	1	3	4	2	4	4	4	4	3.57	3.73
Prospan (PS)	4	16	16	14	8	16	18	16	4.00	4.54
Wabo-Maurer (WM)	35	134	140	108	56	140	138	137	3.82	4.54
Elastomeric Dams										
Delastiflex (CP)	21	58	70	69	59	72	63	46	3.07	3.40
Fel Span (FS)	48	161	178	187	148	174	167	145	3.49	3.56
Onflex (OF)	17	57	68	39	67	63	58	56	3.43	3.63
Transflex (TF)	65	182	205	254	132	191	199	173	3.02	3.11
Unidam (old) (UD)	10	35	42	40	22	32	38	29	3.61	4.11
Unidam (new) (UD)	3	10	12	12	4	12	12	10	3.52	3.92
Waboflex (WF)	29	96	103	116	46	106	97	88	3.40	3.81
Modular										
Acme (AM)	17	66	68	68	30	68	59	65	3.31	3.91
Delastiflex (DE)	3	9	12	12	9	9	12	6	3.29	3.34
Wabo-Maurer (WM)	35	139	143	108	108	143	117	134	3.77	4.13
Finger dams (FD)	22	83	88	87	72	86	86	82	3.98	4.36

NOTE: Ratings were as follows: poor, <3.50; fair, 3.50–3.84; satisfactory, 3.85–4.19; good, 4.20–4.59; excellent, >4.60.

Figure 9 Final rating table from Dahir and Mellott (1987)

The researchers also recommend that a life-cycle cost analysis be conducted, which was beyond the scope of their study.

A Maryland Department of Transportation study was conducted to provide recommendations as to when retrofitting (or removal) of expansion joints could be feasible or advantageous (Wolde-Tinsae, et al, 1988). As in most other studies, common joint types are described as well as their typical faults and defects. A majority of the study is spent determining the feasibility of removing joints all together to create jointless bridge decks, which is accomplished by summarizing the design concepts for new jointless construction, investigating the extension of these concepts to retrofitting, and using finite element analysis to perform case studies of bridges where this process has already been attempted. In cases where the complete removal of a joint is deemed infeasible, the study describes in detail the methods necessary to convert a faulty "open joint" to a "closed joint." Other methods for non-removal retrofitting are described in detail in the recommendations portion of the study.

NCHRP Synthesis of Highway Practice 141, (Burke, 1989), had some of the same goals as this research. The goal of the work was to define the more common bridge joint types in use at the time, gain an understanding of their performance, and look for ways to improve the state of practice. The report lists several joints types; however, it notes that at the time many joints were proprietary. The researcher's ability to thoroughly analyze those joints was therefore somewhat limited. The report includes a discussion of the use of integral construction and its benefits on short and medium span bridges. A list of design considerations and details that can either aid or hinder the performance of joints is provided in

the report's final recommendations. While some of the recommendations apply to older joint types that are not currently used in new designs, many of the general points still apply today.

Prompted by the increasing cost of repairing damaged bridge elements exposed to deicing agents due to joint failure, Johnson and Mcandrew (1993) reported on a study to evaluate and improve the performance of expansion joints in the U.K. Site surveys of 250 joint samples were conducted, in conjunction with a survey that revealed the history of joint replacement, to acquire all of the necessary data, and extensive findings on the current state of each type of joint were reported. The three main joint types that were investigated were asphaltic plug, reinforced elastomeric, and elastomeric in metal runners. Specific recommendations for each joint regarding selection, maintenance, and installation are provided; the quality of workmanship during installation is highlighted as a particularly important parameter that governs performance.

"Improving the Performance of Bridge Expansion Joints", (Barnard and Cuninghame, 1997), is the final report of a working group that was created to investigate the performance of in-service bridge joints across England. Stage 1 of the project was to perform a survey of maintenance authorities on 5 joint types. This resulted in a multitude of performance data that pointed to the Elastomeric in Metal Runners (EMR, i.e. a strip seal) as the best performing joint. Stage 2 was to perform individual site visits to carry out more detailed surveys in order to identify faults and their causes. A table is then compiled that contains the common defects of each joint, and proposed repair methods that correspond to each defect listed. In addition, it provides a list of design requirements the engineer should be considering in joint selection, and outlines a total life cycle cost calculation that it suggests should also affect selection. Details are presented of two different methods for calculating life-cycle cost of a joint, one which is complex and the other which is simpler. Example data and calculations are included in an appendix for ten different joint types and four different road designs. Their results demonstrate how the choice of a joint can be quite different when life-cycle costs are taken into consideration. The authors do, however, discuss some of the challenges of calculating a life-cycle cost, which is heavily dependent on service life, which is difficult to predict. Although it is 15 years old and the study pertains to practice in the UK, the work is very relevant to this project and provides good examples of life-cycle calculations for joints.

Chang and Lee (2001) evaluated the long-term performance of all joint types used by the Indiana Department of Transportation (INDOT). They also investigated the practices of states surrounding Indiana for their experience with those joint types. The research was conducted using questionnaires, interviews, analysis of data provided by INDOT, and onsite assessment of joints. The major result of the work was a ranking of the joint types based on performance. Chang and Lee reported that strip seals and compressions seals performed the best; integral abutments (no joint) also performed well. There was insufficient data to reach any conclusions about the other joint types examined. The investigation into surrounding states revealed varying experiences and practices. Finally, they reported a lack of any uniform standards between the states.

NCHRP Synthesis of Highway Practice 319 (Purvis, 2003), is, although not specifically stated, in many ways a follow-up to NCHRP Synthesis 141. The report surveyed and collected data from 34 states and

other agencies. It contains an in-depth discussion of when, where, and why bridge joints are used. Furthermore it details many of the common issues that agencies face when maintaining joints. Several recommendations are made for maximizing the lifespan of a joint. Finally it states, among other points, that although there is a shift towards integral construction it is unlikely to significantly reduce the number of joints maintained by agencies in the near future.

The AASHTO Maintenance Manual for Roadways and Bridges (*Maintenance*, 2007) includes a brief section that discusses some joint types and the maintenance issues surrounding bridge deck joints. The section references the findings of NCHRP Synthesis 319. The report specifically recommends the use of elastomeric concrete as the header material for joints. It states that the elastomeric material is more durable to the impact of traffic on the joint.

Mogawer and Austerman (2004) reported on the results of a study conducted for the New England Transportation Consortium on the performance of asphaltic plug joints in the six New England states. The objective of the research was to evaluate the asphaltic plug joint for modes of failure, lifespan, and maintenance methods, as well as recommend changes in design considerations. The researchers conducted field investigations as well as lab testing and determined that debonding, cracking, and rutting were the primary failure modes. A major point from their discussions with other states was that there were no uniform standards for design. Furthermore, the report recommended the use of a database to track the performance of joints.

“Sealing of Small Movement Bridge Expansion Joints” (Malla, et al, 2006) presents the results of a study conducted by the University of Connecticut and The New England Transportation Consortium. The first stage of the project was to evaluate the performance of small movement joints used by DOTs/state agencies. Next, a new silicone foam bridge seal was developed and tested in the lab and in real world conditions. The report goes into considerable depth discussing the different joint types, small and large movement, and their properties. It also discusses the development of the new material and recommends more extensive testing. Malla, et al, (2011a) presents the results of a follow-up study on the laboratory and field test results of the new seal material. Also included are the design and installation procedures for the new material.

Marques Lima and Brito (2006) report on the performance of joints in Portugal. The paper identifies the 12 most common road bridge expansion joints used in Portugal, and briefly discusses the low cost of joint installation during initial construction as compared to the high cost of joint replacement when in-service. Data provided shows that joint repair amounts to between 20-30% of the annual bridge management expenditure. It Identifies 7 distinct causes of joint anomalies, and presents some of their causes and evolutions. The data on the joint types, anomalies, and the factors that cause these anomalies are used to support the database that is utilized in a follow-up study.

Wong (2006) is a brief report that cautions against the use of subjective methods in the evaluation of bridge joint performance. The effectiveness of two existing methods of joint evaluation (visual assessments and noise emission) is described, but with growing pressure on evaluation accuracy due to

budget constraints, five new scientific methods of evaluation are proposed. These methods are suggested to be more involved but more accurate, and include temperature, noise level, deflection, and skid resistance measurement. No single method is suggested to be optimal, but the hope is that maintenance officials will select the most appropriate method for more accurately evaluating their particular variety of bridge joint.

"Performance of Polymer Modified Asphalt Bridge Expansion Joints in Low-Temperature Regions" (Yu, et al, 2009), investigates the manipulation of binder content in asphalt plug joints to increase service life in extreme low temperatures (<-10 C). This study identifies two candidates, rubber and thermoplastic rubber, that could act as new binding agents to increase performance. Elongation tests were performed to determine optimal content levels of the binders, and a penetration test was conducted with commercial MEIJA asphalt in addition to asphalt modified by the two binders. For both of the modified binder asphalts, their penetration index and "equivalent brittleness" were higher than commercial asphalt at lower temperatures, indicating softer and better performing materials. Also, a three point bending test was performed to observe the relationship between failure strength, failure strain, and temperature. Commercial asphalt performed the worst with a "brittle point temperature" of -23 C, while thermoplastic rubber displayed -24 C and a combination of thermo rubber and rubber displayed almost -27 C. The mixtures recommended in this study were implemented on a bridge in a cold region with ADT of 6,000, and 7 years later good performance is noted.

Marques Lima and Brito (2010) outlines the logic behind a computer program that functions as a management program for expansion joints. The program contains a database of information regarding these joints, and takes inspection report data on joints as an input. It then uses this data to arrive at a decision regarding potential maintenance, using an algorithm that assigns a degree of urgency to any necessary repair. The program is capable of detecting the type of defect, and offers a suggested maintenance technique.

The goal of "Simplifying Bridge Expansion Joint Design and Maintenance" (Caicedo et al, 2011) was to evaluate the bridge joints used in South Carolina for performance and propose a degradation model for future use. The research looked at every joint type used by South Carolina and did not limit the movement range. The report also evaluated the state of practice of the South Carolina Department of Transportation standards with regards to bridge joints, and made several recommendations. The major findings of the study were that open and poured silicone joints performed the best. The lowest rated joint type was the strip seal. Many of the joint failures that they examined were due to installation issues, particularly when anchoring systems were involved. The researchers made several recommendations: (1) a warranty should be requested from the contractor for the installation of a joint, (2) joint supports should be placed in moderate temperatures and in good quality concrete, and (3) splices should be avoided or placed out of the wheel path.

Malla, et al, (2011b) describes the testing of a new silicon foam sealant. The creation and composition of this sealant are briefly described in the introduction. An extensive series of tests were conducted to determine the performance capabilities of this foam sealant, in comparison with the traditional solid

silicon sealant. The extreme temperature test (where stress, strain and modulus were recorded for temperatures of -36C and 70C) revealed similar trends for both sealants, with little change in performance, and temperature cycle testing generated similar results. Compression set testing revealed a 10% set for the foam and a 1.5% set for the solid sealant. A 24-hr creep test revealed 21% creep for both sealants, and outdoor weathering tests showed no significant deterioration over a 6.5 month period. All tests were performed with a small number of specimens, and while the author instructs caution to be used on generalizing results based on small sample sizes, it states that the presented material should help prompt future studies whose experimental designs would have great statistical power.

To better understand the current practices and performance of small movement (< 2”) expansion joints in the northeast, the Northeast Bridge Preservation Partnership (NEBPP) of the Transportation System Preservation Technical Services Program (TSP2) contracted with the University of Delaware to carry out an investigation and report on the state-of-practice of joints in the 12 agencies of the partnership (Maine, Connecticut, New Hampshire, Vermont, Massachusetts, Rhode Island, New York, New Jersey, Pennsylvania, Delaware, Maryland, and the District of Columbia). The objectives of the research were to determine commonly used expansion joints in the North East, gather data on the past performance of joints, and examine the state-of-practice of joint design, maintenance, repair, and replacement. The results of the study are reported in Milner and Shenton (2014). Key findings of the study were: (1) the most common joint used by the NEBPP members for new construction is the strip seal; the most common joints used for maintenance and repair are the asphalt plug, strip seal, and poured silicone; (2) the most commonly avoided joint is the compression seal; (3) the majority of NEBPP members use manufacturer specifications to determine joint sizes; (4) the average lifespan of joints in new construction is from 5 to 15 years, depending on the type of joint and maintenance practices; the average lifespan for maintenance or repair is 2 to 10 years, and (5) the two leading causes of joint failure were improper installation and lack of preventative maintenance.

As part of the literature survey the research team also searched for literature, reports, and data on small movement expansion joints and their use in other applications and industries, e.g., in stadiums and arenas. No other information was found that was considered of value to the project. The research team also had many conversations with manufacturers and suppliers of small movement expansion joints, who sell their products in these other industries; however, none offered any information about those applications that was considered useful for the project.

Finally, while not summarized here, design manuals and maintenance manuals, where available, were collected from many of the state agencies. Table 1 shows the states for which manuals were obtained.

Table 1 Manuals obtained from state agencies

State	Design Manual	Maintenance Manual
Alabama	✓	✓
Alaska		
Arizona	✓	
Arkansas		
California		✓
Colorado	✓	
Connecticut		
Delaware	✓	✓
Florida	✓	✓
Georgia	✓	✓
Hawaii		✓
Idaho	✓	
Illinois	✓	
Indiana		
Iowa	✓	✓
Kansas		
Kentucky	✓	
Louisiana	✓	
Maine	✓	
Maryland	✓	
Massachusetts	✓	
Michigan		✓
Minnesota	✓	✓
Mississippi	✓	
Missouri		
Montana	✓	✓
Nebraska	✓	
Nevada	✓	✓
New Hampshire	✓	
New Jersey	✓	
New Mexico	✓	
New York	✓	✓
North Carolina	✓	
North Dakota	✓	
Ohio	✓	✓
Oklahoma		
Oregon	✓	
Pennsylvania	✓	
Rhode Island	✓	
South Carolina		
South Dakota	✓	
Tennessee		
Texas	✓	

Utah		✓
Vermont	✓	
Virginia		
Washington	✓	
Washington, DC	✓	
West Virginia	✓	
Wisconsin	✓	
Wyoming		

3. Stakeholder Survey

The objective of Task 2 was to gather information from owners and other stakeholders on their practices and experiences with small movement expansion joints. To this end, an online survey was developed using the University of Delaware's Qualtrics survey system. The survey was designed to be taken by four main stakeholder groups: (1) bridge owners, (2) bridge consultants, (3) contractors involved in construction of new bridges, and maintenance and repair of existing bridges, and (4) suppliers and manufacturers of small movement bridge expansion joints. A single survey was designed for all stakeholders, with control logic directing each to the appropriate questions. Some of the questions were the same for all four groups, but because each has a different perspective with respect to SMEJ's the respondent was directed to a group of questions tailored to their role in the industry. The survey is included in Appendix A.

Distribution of the survey was completed via email to the various stakeholders. The names and contact information of the stakeholders were obtained from a number of sources. These included:

- AASHTO Subcommittee on Maintenance (SCOM)
- AASHTO Subcommittee on Bridges and Structures (SCOBS)
- AASHTO Transportation System Preservation Technical Services Program (TSP-2), Bridge Preservation Partnership, members of the Boards of the four regional partnerships
- Attendee list from the 2014 National Bridge Preservation Partnership Conference
- Attendee lists from the four most recent Regional Bridge Preservation Partnership annual meetings
- Attendee list from the 2014 International Bridge Conference
- Contractor and supplier contacts provided by bridge owners in the survey, obtained from expos at conferences, and through online searches

Results

It is difficult to report an exact response rate because of the way the survey was administered, i.e., anyone who had access to the web link was free to complete the survey. It was setup this way so that the link could be forwarded to another person for completing, since often times the first contact in an agency or company may not be the best person to complete the survey. Those receiving the email invitation were instructed to forward the link along to another person if they felt their designee was more knowledgeable of SMEJ's. They were also instructed that they could forward it to multiple people for completing. Thus, it is difficult to say exactly how many individuals received an invitation to take the survey; however, a total of 108 responses were received.

The greatest response by far was from bridge owners, followed by consultants, then suppliers, and finally contractors (Table 2). The largest number of invitations, whether directly or by second hand distribution, went to bridge owners. Also, the number of joint suppliers/manufacturers is relatively small; contractors were the least responsive.

Table 3 shows the state agencies who completed the survey. Because practices on the design side can be different from those on the maintenance and operation side of an agency, responses were requested from both. Owners were asked to report what side they represented, and the results are shown in Table 3 (each check represents a unique survey response). Responses were received from 37 of the state agencies, with 31 responses coming from the design side and 19 coming from the maintenance and operations side. Seven owners reported being in an "other" category; comments usually meant representing both the design and maintenance/operations side. The balance of those who responded as a bridge owner did not select an area. One can see the responses are fairly evenly distributed and representative of both sides.

Table 2 Distribution of completed surveys by stakeholder group

Stakeholder	**Number of completed surveys**
Bridge owners	73
Consultants	15
Contractors	6
Suppliers/manufacturers	14

Table 3 Surveys completed by state agencies

State	**Design**	**Maintenance**	**Other**
Alabama	✓	✓	
Alaska	✓		
Arizona	✓	✓	
Arkansas			
California	✓✓		
Colorado			✓
Connecticut		✓✓	
Delaware	✓	✓✓	
Florida		✓	✓
Georgia			
Hawaii	✓		
Idaho			
Illinois			
Indiana		✓	
Iowa		✓	✓
Kansas	✓		✓
Kentucky			
Louisiana			
Maine			
Maryland		✓	
Massachusetts	✓		
Michigan		✓	✓
Minnesota	✓	✓	
Mississippi			

Missouri	✓	✓	
Montana			
Nebraska			✓
Nevada	✓		
New Hampshire			
New Jersey	✓✓	✓	
New Mexico	✓		
New York	✓✓		
North Carolina			
North Dakota	✓		
Ohio		✓	
Oklahoma	✓	✓	
Oregon	✓		
Pennsylvania	✓✓		
Rhode Island	✓		✓
South Carolina	✓		
South Dakota	✓		
Tennessee	✓		
Texas	✓		
Utah	✓		
Vermont			
Virginia		✓	
Washington	✓	✓	
Washington, DC			
West Virginia			
Wisconsin	✓	✓	
Wyoming	✓		

Types of Joints Used

Several questions in the survey were designed to determine (1) what types of SMEJ's were being used by bridge owners, for new construction and for maintenance, repair and replacement, (2) the owner's level of satisfaction with the joints, and (3) the typical service life achieved with each of the joints. The questions were divided into joint types and header material/design. Presented in Figure 10 through Figure 13 are the results of these questions.

Figure 10 shows the response for joints used in new construction. In each of these figures the top graph summarizes if the joint is regularly used, is growing in potential but currently has limited use, is being phased out or is no longer used, and finally if it has never been used. Each bar represents a different type of joint, which are shown at the bottom of the figure. The middle graph shows the level of satisfaction, where the question offered five choices ranging from very satisfied to very dissatisfied. The bottom graph shows the reported life span of the joint; the square marker denotes the average age and

the vertical bar denotes +/- one standard deviation of the reported life. Participants provided feedback only on the joints they had experience with, thus the number of responses varies for each joint.

Far and away, the most common type of SMEJ being used today for new construction is the strip seal, with 48 owners responding that they use it regularly or its use is growing. The next most frequently used joints are pourable silicone and then compression seals. The joint used least regularly for new construction is the open cell foam, which are relatively new to the market, followed by the asphalt plug joint. The open cell foam has the largest fraction of users reporting it has never been used, but it has a very high response for growing in potential, following just behind performed "ʌ" and "M". Many users also report having never used the asphalt plug, closed cell foam, open cell foam, and preformed "ʌ" and "M" joints. Turning to level of satisfaction, the strip seal clearly ranks highest when compared to all of the other seals; just over 12% of the 57 owners who responded to this question stating they were dissatisfied with the strip seal. Most of the other seals have levels of satisfaction of "satisfied" somewhere in the 30-45% range. Nineteen owners responded to open cell foam, with a total of six saying they were satisfied or very satisfied with the material. Overall dissatisfaction was highest for the asphalt plug joint, elastomeric cellular compression seals, pourable silicone, closed cell foam, and various types of open joints. Presented in Figure 10(c.) is the average life span as reported by the respondents. The open joint is reported to have the longest average life, averaging close to 23 years, followed by the strip seal at an average of about 16 years. Most all of the other seals average less than 10 years.

A similar set of graphs are shown in Figure 11 for joints used for maintenance, repair and replacement. The trends are very similar to those for new construction. The strip seal is once again used most frequently followed by pourable silicone and elastomeric cellular compression seals. Any type of open joint, however, is used less frequently for maintenance, repair and replacement. There is a slight increase in the use of the asphalt plug, elastomeric cellular, pourable silicone, preformed "ʌ" and "M", and open cell foam joints for maintenance, as compared to new construction. Almost half the respondents reported never having used open cell foam for maintenance, repair or replacement, but once again it is growing in potential. The level of satisfaction with the various joints is almost identical to that reported for use in new construction: satisfaction is highest again for the strip seal, and overall lowest for asphalt plug, elastomeric cellular, pourable silicone, closed cell foam, and open joints. The reported life of joints when used for maintenance, repair and replacement is almost identical to that for new construction: it is highest for open joints and strip seals, and lower for all other joints.

Figure 12 and Figure 13 show similar graphs for headers for new construction and maintenance, repair and replacement. The most frequently used design for new construction consists of regular concrete and armored, followed by elastomeric/polymeric concrete and non-Portland based concrete. More than half the respondents reported never having used Non-Portland based concrete for new construction. Figure 12(b) shows that the level for satisfaction for all of these materials/designs is fairly equal across the board; however, it is highest for armored, and lowest for non-Portland based or elastomeric/polymeric, depending on how one interprets the results. Armored and regular concrete have average life expectancies of 17-18 years, with the others being somewhat lower. Figure 13 shows

the results for maintenance, repair and replacement. In this case the use is about equal for all of the material/designs. Compared to new construction, non-Portand concrete and elastomeric/polymeric concrete are being used more frequently and are growing in potential. The level of satisfaction is about the same as for new construction, with only a slight apparent increase in satisfaction for the elastomeric and polymeric concretes. Finally, the average life is highest for armored, followed by regular concrete, elastomeric/polymeric and finally non-Portland based concrete.

These results provide a good picture of the joints and header materials being used across the country, and the typical life span of the joints. The results are not dramatically different between new construction, and maintenance, repair and replacement.

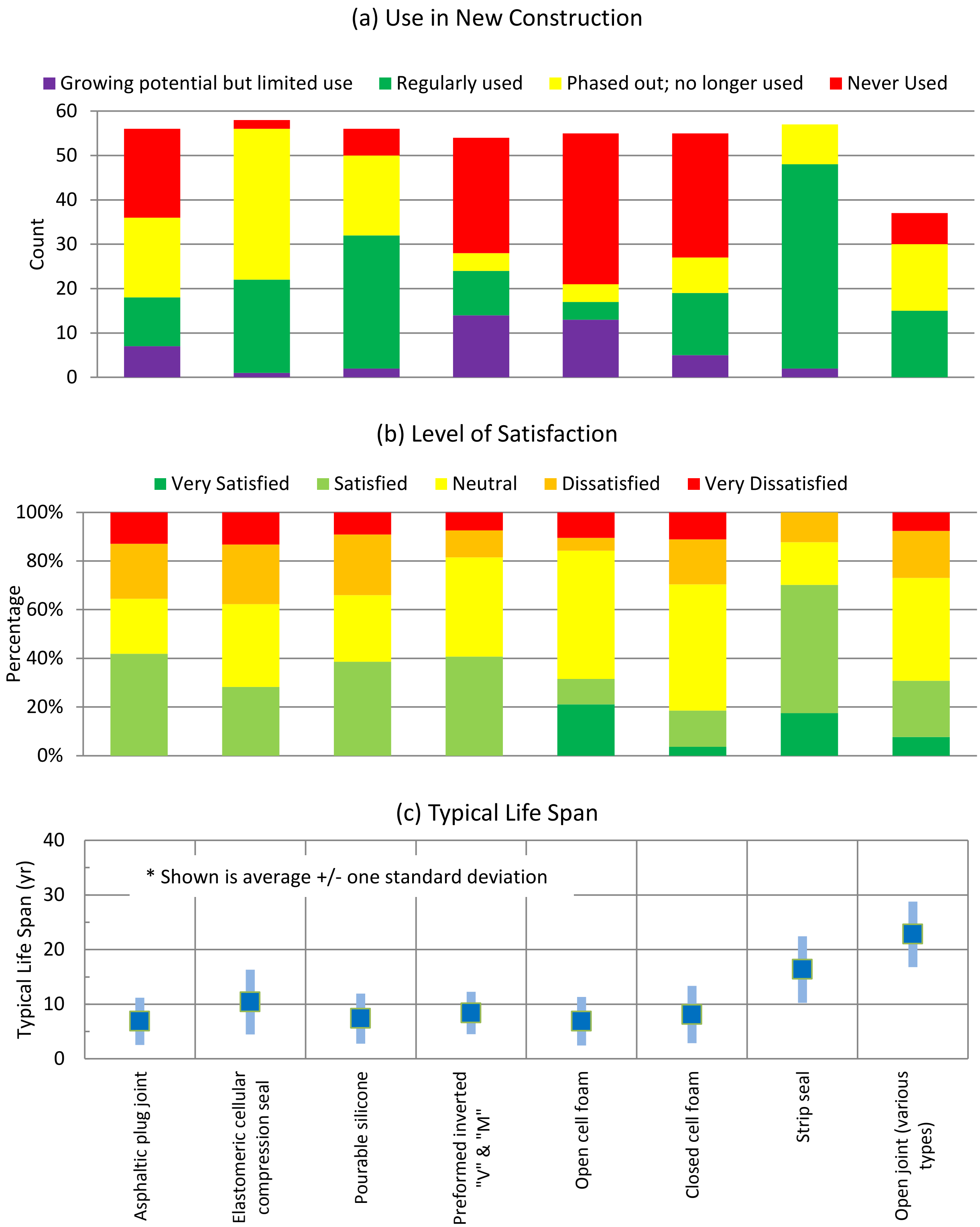


Figure 10 Survey responses: Bridge Owners experience with joints in new construction

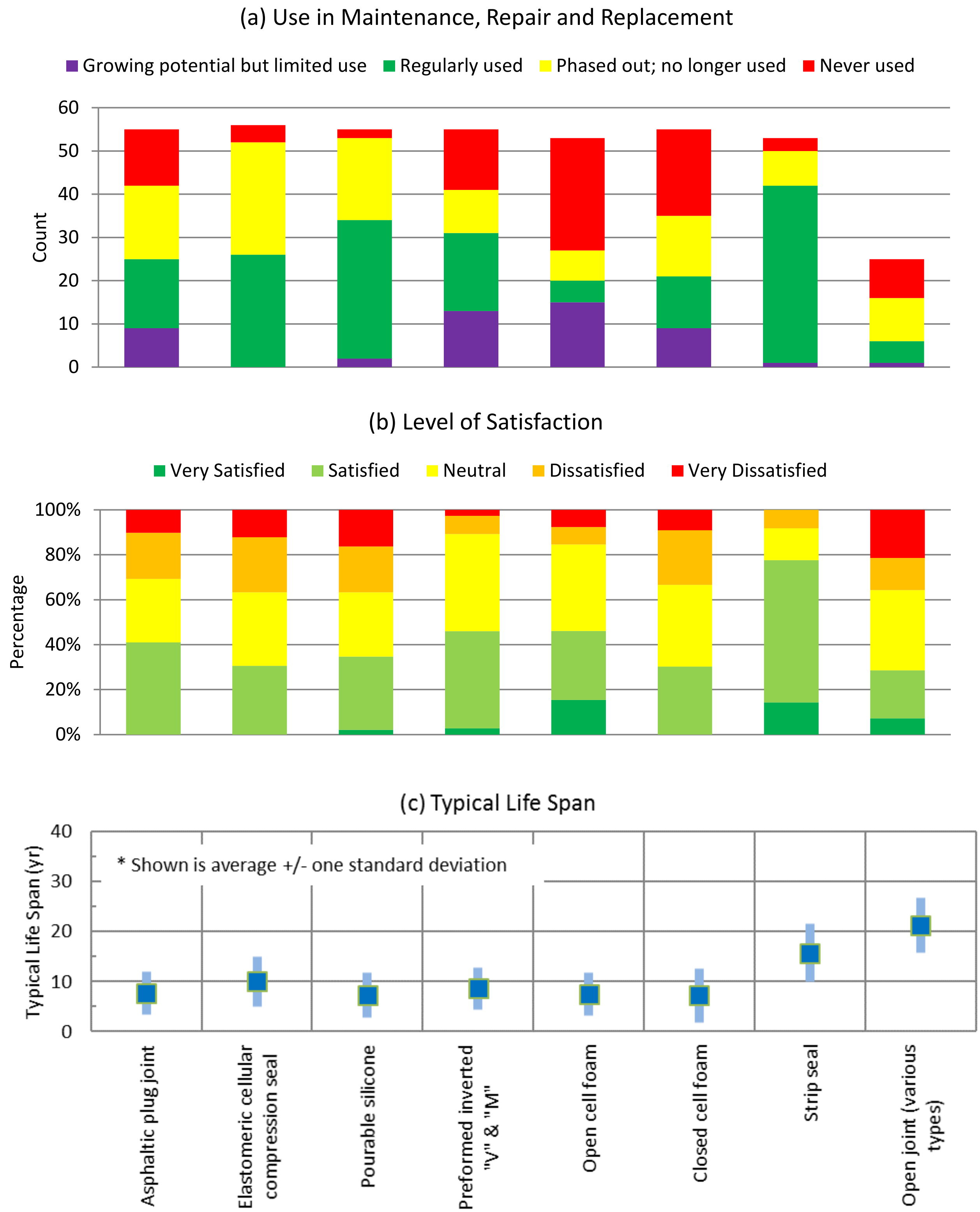


Figure 11 Survey responses: Bridge Owners experience with joints for maintenance, repair and replacement

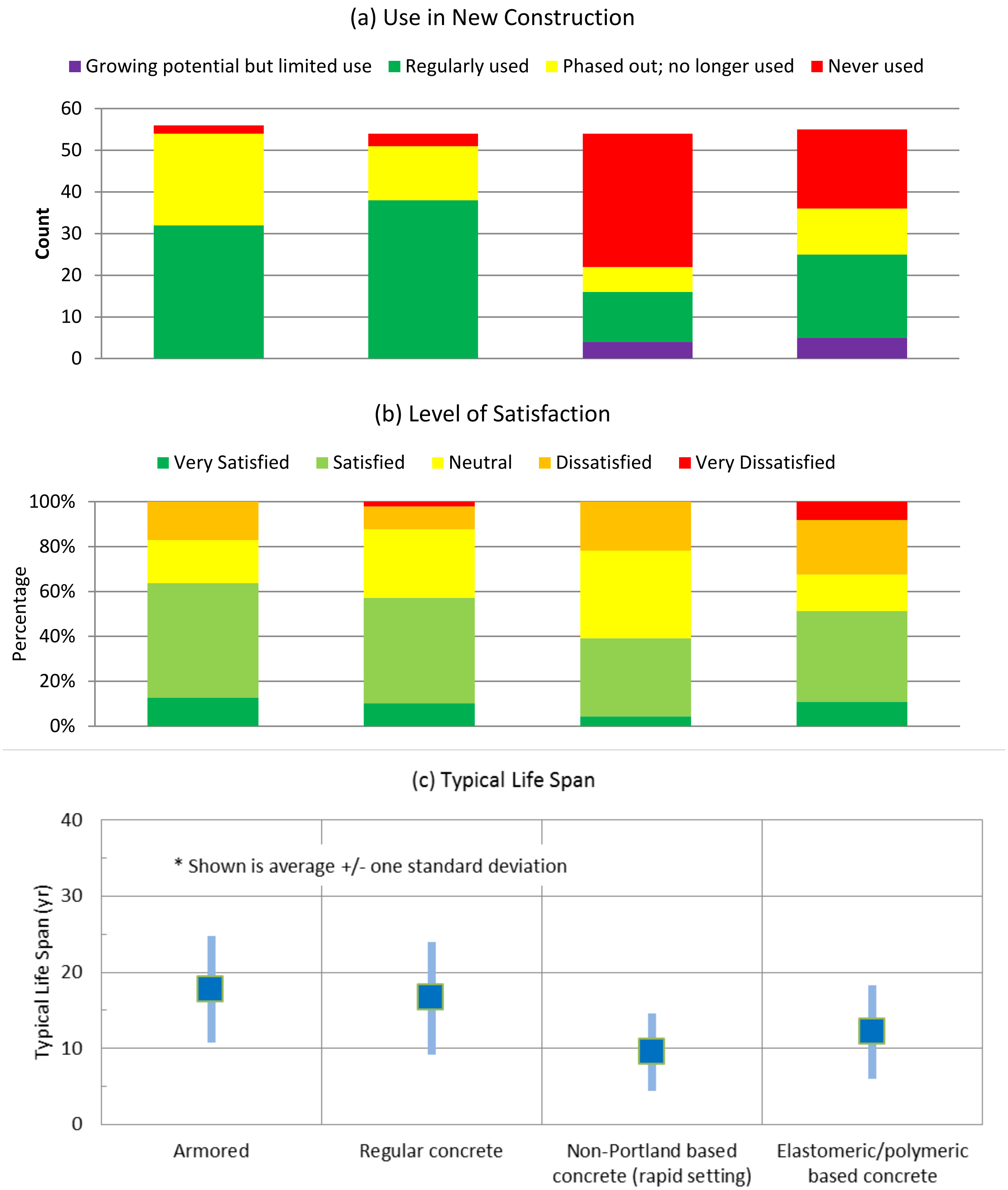


Figure 12 Survey responses: Bridge Owners experience with headers in new construction

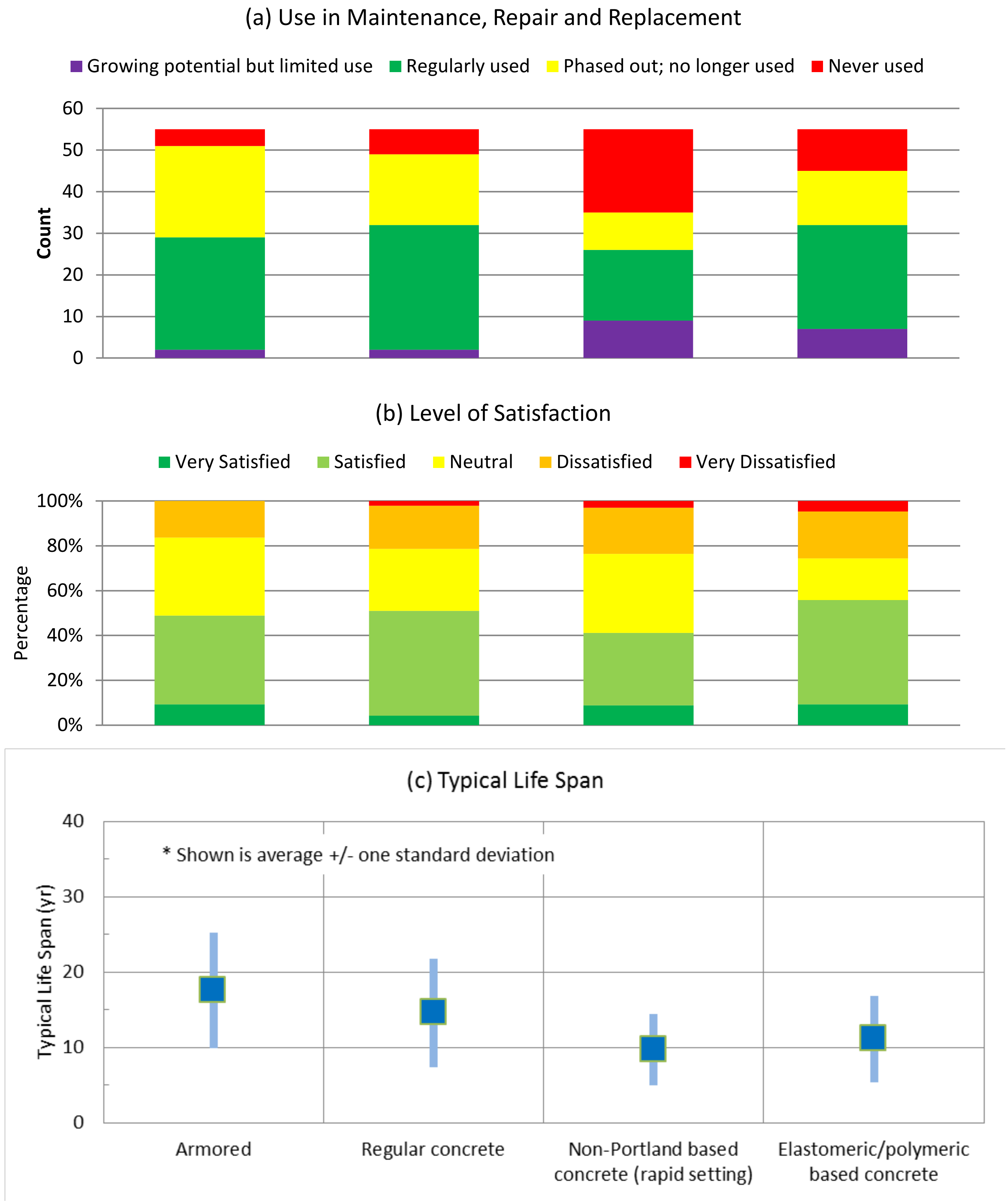


Figure 13 Survey responses: Bridge Owners experience with headers for maintenance, repair and replacement

When asked if they try to eliminate joints in new construction, bridge owners responded: 4% said they are eliminating all joints, 54% are eliminating most joints, and 7% said they are not eliminating any joints. The balance (35%) are eliminating some or even half of the joints. When asked the same question for existing bridges, owners responded: none said they are eliminating all joints, 30% are eliminating most joints, and 22% said they are not eliminating any joints. The balance (49%) are eliminating some or even half of the joints.

When asked if they have an established process for testing or approving new SMEJ's, 36% of bridge owners said they do and 64% said they do not. Eleven out of 17 that do have a process reported some type of field trial of the joint, with the time of the trial typically being one year.

Joint Failure Mechanisms

One section of the survey addressed failure modes of common joints. Respondents were asked to describe, in their own words, the modes of failure of the various common SMEJs. To summarize the results, the terms used to describe failure for a particular joint were first compiled from all of the responses. Terms that were similar were considered the same and described with one single adjective or phrase. The number of times a particular word or phrase was used to describe failure was then totaled for all the responses. The terms were then listed in order of decreasing frequency. These results are shown in Table 4. The modes of failure are unique for each type of joint, although there are some in common for joints that are similar in construction. For example, "Bond failure/separation of joint from header," was mentioned for all joints except open; "tearing" was another term used to describe a mode of failure for several types of joint. The number of times a mode was mentioned is also a strong indication that this is a common and frequent mode of failure. For example, "tearing" was mentioned 25 times for strip seal, suggesting that it is a frequently observed failure mode. Likewise, "bond failure/separation of joint from header" was mentioned 25 times for poured silicon, suggesting that it too is common.

It is interesting to note that the first and most frequent failure mechanism noted for all of the joints seals that are bonded or anchored to the header is "bond failure" or "tearing." This would indicate excessive tension in the seal. This could be a design issue (incorrect sizing of the seal), a materials issue (improper material tests), or an installation issue (a correctly sized seal installed in the summer when the gap is closed).

Table 4 Joint failure modes

Joint	**Modes of Failure (times reported in survey comments)**
Asphaltic Plug Joint	Bond Failure/Separation of Joint from Header (10), Heave (9), Cracking (8), Rutting (8), Improper Material Mix (1), Misaligned Centering Pins (1), Insufficient Depth (1), Deterioration (1), Blowouts (1), Porous Asphalt (1).
Elastomeric cellular compression Seal	Bond Failure/Separation of Joint from Header (18), Seal Falling Out (14), Debris Impaction (10), Tearing (9), Loss of Rebound (5), Cracking (5), Snowplow Impact (3), Header Failure (2), Poor

	Installation (2).
Pourable Silicone Seal	Bond Failure/Separation of Joint from Header (25), Tearing (6), Debris Impaction (5), Cracking (3), Tire Wearing (3), Snowplow Impact (3), Header Failure (2), Poor Surface Preparation (2), Backer Rod Movement (1), Seal Falling Out (1).
Preformed "ʌ" and "M" type	Bond Failure/Separation of Joint from Header (18), Tearing (5), Debris Impaction (4), Tire Wearing (3), Poor Installation (2), Cracking (1), Header Failure (1), Seal Falling Out (1).
Open Cell Foam	Bond Failure/Separation of Joint from Header (7), Debris Impaction (3), Improper Sizing (1), Tire Wearing (1).
Closed Cell Foam	Bond Failure/Separation of Joint from Header (12), Improper Sizing (3), Debris Impaction (3), Compression Set (1), Deterioration (1), Tearing (1), Loss of Elastic Properties Due to Heat (1).
Strip Seal	Tearing (24), Debris Impaction (14), Extrusion/Seal Pushed out of Joint (13), Header Failure (9), Bond Failure/Separation of Joint from Header (4), Cracking (3), Snowplow Impact (3).
Finger/Tooth Joint	Clogged Trough (3), Anchor Bolt Deterioration (2), Teeth Breaking (2), Misaligned Teeth (1), Snowplow Impact (1).

Presented in the proposed guidelines (separate document), is a compilation of photographs of many of these failure modes, organized by type of joint.

Strawman Performance Metrics

A major section of the survey was devoted to gathering feedback on perspective performance metrics for joints. To do this the AASHTO LRFD Bridge Design Specification as used as a guide, noting that the primary design objectives that are relevant to joints are serviceability, constructability, and economy. Thus, strawman metrics were formulated around durability, inspectability, maintainability, constructability, rideability, and economy. Within each one of these categories one or more metrics were proposed, and for each two questions were posed: (1) how easy or difficult would it be to gather the data needed to report the metric, and (2) how effective the measure would be as a performance metric. Participants were introduced to this section of the survey with the following instructions:

"One goal of NCHRP 12-100 is to develop performance metrics for small movement expansion joints. The research team is initially focusing on the LRFD Design Specifications as a guide. Below are a series of potential performance metrics for consideration. They are centered around Serviceability, Constructability, and Economy. Note that these are just concepts/ideas that are being presented to gather feedback on how effective such a measure might be, and how difficult it would be to gather the data needed to evaluate performance. For each one please indicate how easy or difficult it would be to gather and report the data needed for the metric, also indicate how effective you think the metric would be as a performance metric."

The full suite of strawman metrics is shown in Table 5. Each metric has been given a letter designation, A through N, for easy reference in this discussion. For "Data Collection" the survey offered 3 choices: "1-difficult", "2-neutral", and "3-easy." For "Effectiveness" the survey offered 5 choices: "1-very effective," "2-effective," "3-neural," "4-ineffective," and "5-very ineffective." In the columns to the right of the metrics are the average scores from owners, consultants, suppliers, and contractors.

From the owner's perspective the "easiest" metrics to collect data for were "Is the joint easily inspected" and "Can a leak be detected." The most difficult was "life-cycle cost," with an average score of 1.45. Consultants felt the easiest would be "Is the joint easily inspected" and the most difficult would be "International Roughness Index" and "life-cycle cost." Suppliers responded "Is the joint easily cleaned" as the easiest to collect data for and "life-cycle cost" as the most difficult. Finally, contractors felt the easiest would be "service life," "is the joint easily cleaned," and "constructability," with all equal scores of 2.75. The most difficult would be "life-cycle cost." Thus there is reasonable consensus among these stakeholder groups of which of the proposed metrics would be the easiest to gather data for, and which would be the most difficult.

Regarding effectiveness, owners responded that the most effective metric was "service life of the joint," with an average score of 1.89 on the 5-point scale. The least effective was "International Roughness index," with an average score of 3.17. "Does the quality of the installation affect performance?" received the best "effectiveness" score (1.55) from the consultants; "service life of the joint" and "life-cycle cost" ranked second most effective for this group. The least effective for that group was "International Roughness Index." The suppliers rated "does the joint effect ride quality" the best for effectiveness, with a close second being "Is the joint easily replaced." They rated "Percentage of deficient joints on a highway classification, perhaps groups by ADT" as the least effective, with a score of 2.64. Finally, the contractors ranked "can a leak be detected," and "does the quality of the installation affect joint performance," as the most effective, and "is the joint easily inspected" and all of the maintainability metrics as least effective.

An ideal performance metric would be one for which data collection is easy, and the metric is very effective in describing performance. To better judge how the proposed metrics compare, a plot of the average results is shown in Figure 14, in which average data collection is plotted on the x-axis and average effectiveness is plotted on the y-axis. The Owner responses are shown by a white circular marker, the Consultants by a red square marker, the Suppliers by a yellow triangular marker, and the Contractors by a black diamond. Each marker represents one metric from the four stakeholder groups from Table 5. Ideal metrics would fall in the lower right hand quadrant of the plot, and the non-ideal would fall in the upper left quadrant. One can see that many of the metrics fall towards the bottom half of the plot, suggesting that in general the participants felt many metrics could be effective. However, there is not one metric that falls clearly to the right and bottom of the plot, i.e., is the ideal metric. It is interesting that in general the consultants, suppliers, and contractors ranked the metrics easier and more effective than owners did. Figure 15 to Figure 18 show individually each of the stakeholder group's responses.

Referring to Figure 15 for the owners, the five most promising metrics are:

- N – Life-cycle cost
- M – does quality of installation affect performance
- A – service life of the joint
- D- can a leak be detected, and
- C – is the joint easily inspected

Figure 16 shows just the suppliers response. The five that scored the best for this group were:

- N – Life-cycle cost
- L – constructability for repair
- I – does the joint effect ride quality
- G – is the joint easily repaired, and
- F – is the joint easily cleaned

Referring to Figure 17 for the consultants, the five that scored the best were:

- N – Life-cycle cost
- M – does quality of installation affect performance
- B – service life of the substructure
- I – does the joint effect ride quality, and
- A – service life of the joint

Finally, referring to Figure 18 for the contractors, the five that scored the best were:

- M – does quality of installation affect performance
- B – service life of the substructure
- D- can a leak be detected
- A – service life of the joint (tied with K)
- L – constructability for repair
- K – constructability (tied with A)

Clearly three groups view A – "life-cycle cost" as a potential performance metric. Owners, consultants, and contractors also show consensus on two other metrics: M - "does quality of the installation affect performance" and A - "service life of the joint." Consultants and suppliers both agree that I – "does the joint effect ride quality" has potential. These results collectively offered preliminary suggestions of what the stakeholders believe would be good performance metrics, and ones that could be implementable.

Three of four stakeholder groups agree that "life cycle cost" has potential as a performance metric. It received a very good effectiveness scores; however, all three groups scored it very low in terms of data collection, indicating participants believe collecting life-cycle data would be very difficult. The survey specifically asked bridge owners if they maintain life-cycle data on joints. Of the 49 responses, 46

answered “No.” A follow-up question asked respondents to describe when, how, and where life-cycle cost data is stored. Two responses were provided, one saying “at bridge inspection period” and another “The Bridge Scoping Engineer keeps data related to life cycle costs and updates and shares this data with region bridge engineers.” The research team followed up with these two agencies to learn more about the life-cycle data they have collected: it determined that each had misinterpreted the question and in fact neither collected life-cycle data. Thus it was determined that of the agencies that responded to the survey, none currently collect and maintain life-cycle cost data on SMEJ’s.

Respondents were also asked to provide their own ideas and suggestions for potential performance metrics. A total of 17 responses were received from among the 108 surveys returned. Of those there were only a few unique ideas that were not essentially captured by the strawman metrics proposed in the survey. The unique ideas were:

- Flexibility to accommodate nonparallel openings for replacement and offers wide range of movement
- How does ADT and truck traffic affect joint performance
- Can a partial repair be made or does the entire joint need to be replaced?
- How does the joint hold up under varying environmental conditions – rain, ice, use of sand and deicing materials, studded tires
- Does the joint provide watertight transitions to curbs and walls?

Respondents were asked to provide any information they had on guidelines and standards for maintenance, repair, and replacement of SMEJ’s. Bridge owners were first asked:

> “Does your agency have guidelines or specifications for maintenance of SMEJs, repair of SMEJ's, replacement of SMEJ's? If so please describe these and provide a reference where possible”

Of the 45 responses, 51% responded “No,” 24% referred to some type of agency manual, specification, or document, 4% mentioned documents/manuals under development, and the balance provided various other responses.

Bridge owners were then asked:

> “Do you have, have access to, or are aware of other guidelines/specifications for maintenance, repair, or replacement of SMEJ's, from for example, consultants, contractors, vendors? If so please provide a copy of or a reference to the guideline/specification”

Of the 40 responses, 67% said “no,” 15% referred to a vendor or manufacturer document, and the balance provided various other responses.

When asked “What procedures or techniques are used by your agency to maintain SMEJ’s?”, 31% of owners responded by describing some type of cleaning or washing procedure. 25% responded by

describing some type of, what has been defined here as a repair procedure, such as repairing or replacing the seal. 13% responded that they do not maintain their joints. The balance responded with a variety of comments such as eliminate the joint, inspect the joint, do as-needed repairs, or other.

Consultants, suppliers, and contractors were asked:

> “Does your company have guidelines or specifications for maintenance, repair, or replacement of SMEJs? If so please describe these and provide a reference where possible.”

The responses from these stakeholder groups to this question usually referred to agency specifications or manufacturer specifications. Of the eleven suppliers that responded to the question, 7 said they have their own specifications.

Table 5 Survey average response to strawman performance metrics

Question	Designation	Owners		Consultants		Suppliers		Contractors	
		Data Collection[1]	Effectiveness[2]	Data Collection[1]	Effectiveness[2]	Data Collection[1]	Effectiveness[2]	Data Collection[1]	Effectiveness[2]
Q39. Serviceability: Durability									
Q39a. Service life of the joint - how long the joint lasts before it begins to leak (reported in months or years)	A	1.98	1.89	2.64	1.64	2.36	2.27	2.75	2
Q39b. Service life of the substructure - how long before beam ends, pier caps, pedestals and columns begin to deteriorate because of leaking joints (reported in months or years)	B	1.94	2.47	2.4	1.7	1.82	2.45	2.25	2
Q40. Serviceability: Inspectability									
Q40a. Is the joint easily inspected? (reported as yes/no or on a numeric scale)	C	2.62	2.41	2.91	2.36	2.36	2.18	2.25	2.5
Q40b. Can a leak be detected? (reported as yes/no or on a numeric scale)	D	2.4	2.09	2.9	2.0	2.45	2.09	2.25	1.75
Q40c. Percentage of deficient joints on a highway classification, perhaps grouped by ADT	E	2.02	2.7	2.2	2.6	1.82	2.64	2.25	2.25
Q41. Serviceability: Maintainability									
Q41a. Cleaning - is the joint easily cleaned? (reported as yes/no or on a numeric scale)	F	2.19	2.53	2.45	2.09	2.73	1.91	2.75	2.5
Q41b. Repair - is the joint easily repaired? (reported as yes/no or on a numeric scale)	G	1.94	2.43	2.3	1.9	2.64	1.64	2	2.5
Q41c. Replace - is the joint easily replaced? (reported as yes/no or on a numeric scale)	H	1.96	2.38	2.3	2.1	2.55	1.73	2	2.5
Q42. Serviceability: Rideability									
Q42a. Does the joint effect ride quality (e.g., seals protrude above road surface; prone to plow damage)? (reported as yes/no or on a numeric value)	I	2.13	2.72	2.55	1.82	2.5	1.7	2.25	2.25
Q42b. International Roughness Index (IRI)	J	1.66	3.17	1.5	3.11	2.1	2.6	2	2.75
Q43. Constructability									
Q43a. Constructability (new construction) - considering time to install, equipment required, training needs, sizing, personnel safety needs, clean-up (reported on a numeric scale)	K	1.87	2.58	2.36	2.18	2.1	2.0	2.75	2
Q43b. Constructability (rehabilitation and repair) - considering time to install, equipment required, training needs, sizing, personnel safety needs, clean-up (reported on a numeric scale)	L	1.89	2.48	2.18	1.91	2.2	1.8	3	2
Q43c. Does quality of the installation affect joint performance?	M	1.67	2.02	2.0	1.55	2.2	1.9	2.5	1.75

(reported as no/somewhat/yes or on a numeric scale)									
Q44. Economy: life-cycle cost.									
Q44. This would include first costs, inspection and maintenance costs, replacement costs, and substructure rehabilitation costs for any leakage damage between replacements	N	1.45	2.09	1.55	1.7	1.8	1.8	1.75	2.25

1 – Data Collection scale: 1-difficult, 3-easy

2-Effectiveness scale: 1-very effective, 5-very ineffective

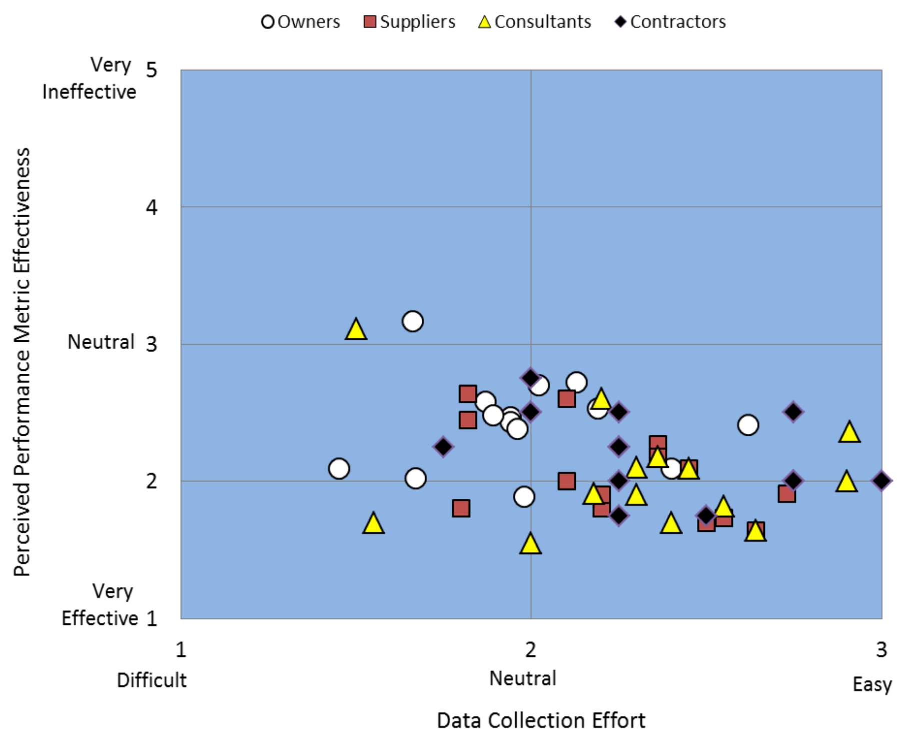


Figure 14 Survey response: summary of response to strawman performance metrics

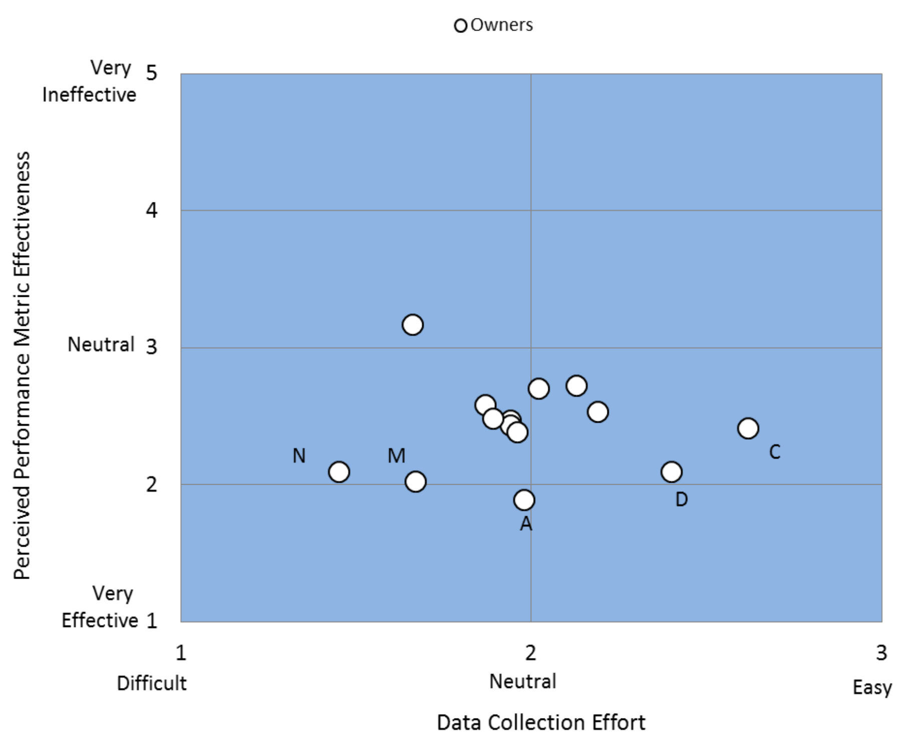


Figure 15 Owner response to strawman performance metrics

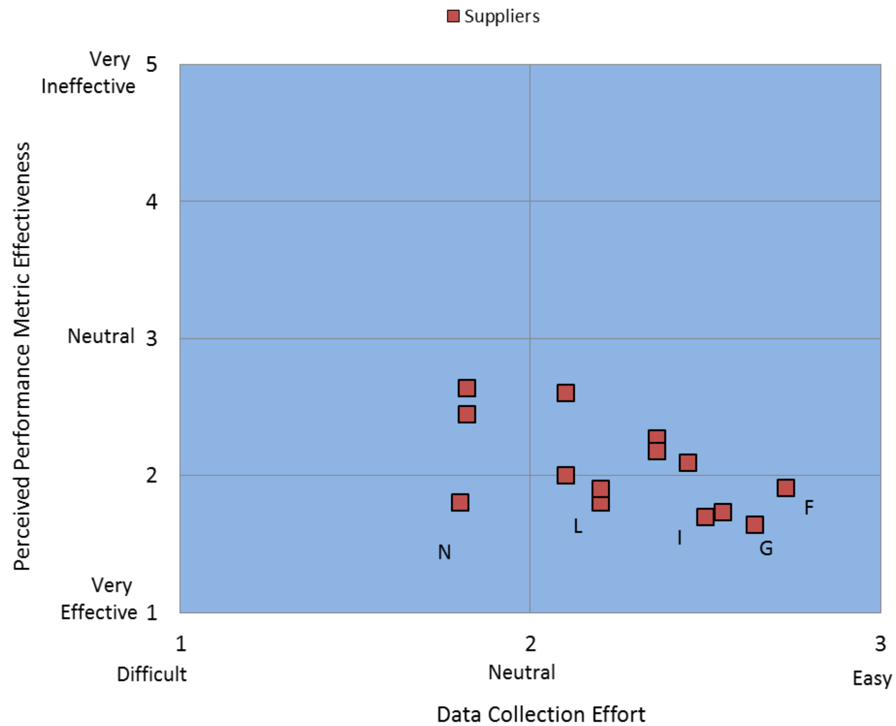


Figure 16 Supplier response to strawman performance metrics

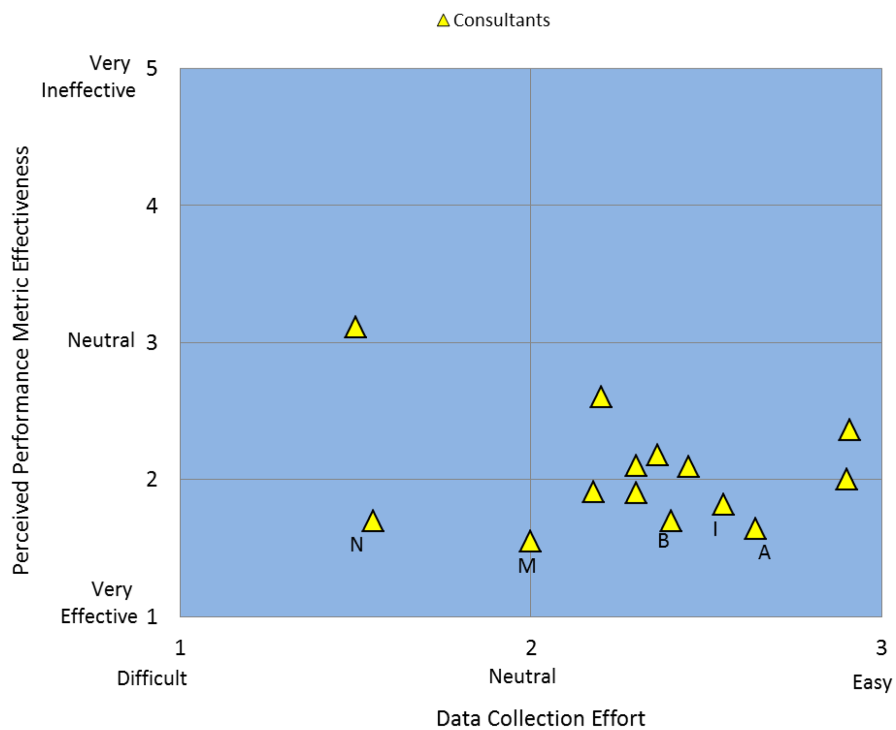


Figure 17 Consultant response to strawman performance metrics

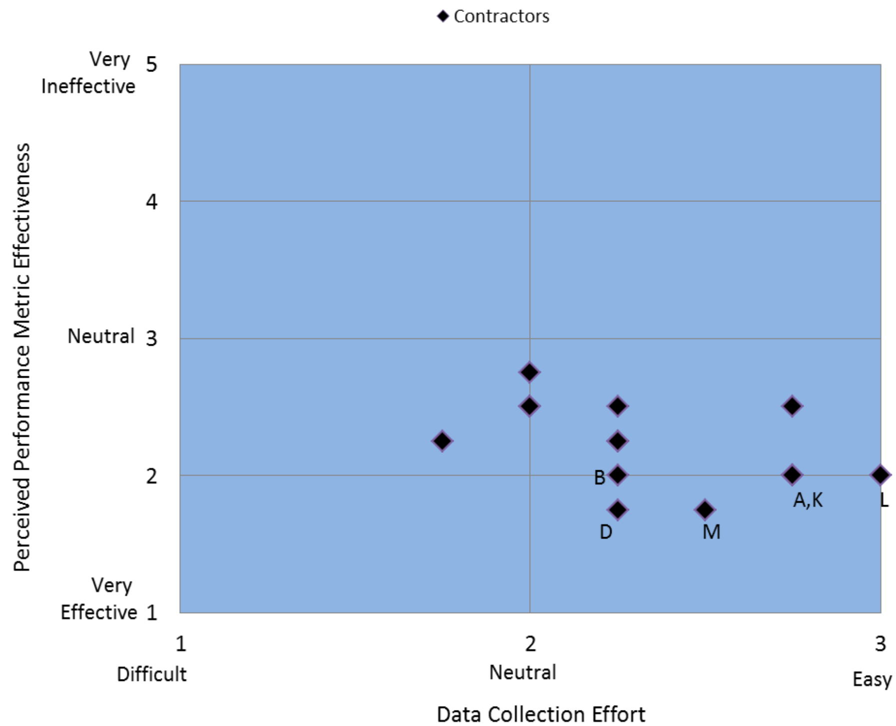


Figure 18 Contractor response to strawman performance metrics

4. Data Gathering and Studies to Support Development of the Guidelines

The information provided in this chapter summarizes various tasks conducted under Task 4 of the project that lead to the development of the procedures for maintenance, repair, and replacement of SMEJ’s.

Gathering and Synthesizing Best Practices

The survey results provided a good sense of the state-of-practice of maintenance, repair, and replacement of small movement bridge joints. It shows that there are joints that are performing better than others, that have better track records, and for one reason or another states have preferences for using them in new construction or for replacement. This section describes the various steps that were taken to learn more about best practices in use today that have led to positive experiences with SMEJ’s.

Very often an owner agency’s bridge design manual or bridge maintenance manual will have information on small movement joints. A review of these documents provides a good starting point for assessing the current standard of practice. An effort was made to locate and obtain a copy of design and maintenance manuals from as many owner agencies as possible; those that were located are shown in Table 1. Each of these manuals was reviewed for information on joints that would be relevant to developing the guidelines. Those that had information of any significance were noted and the relevant sections were extracted from the manual. A number of agencies had substantive material that provided guidance; however, all are unique and vary quite significantly in their focus, length, and organization. There is useful information in each of them, but none stood out as being comprehensive: parts or sections of these excerpts could be incorporated into the final guidelines.

A careful review of the survey results showed that certain owners reported being “satisfied” or “very satisfied” with the performance of specific joints, for either new constructions or for replacement. These owners were identified and grouped according to joint type. California, Maryland, Ohio, Wyoming, and the NJTA, for example, reported being very satisfied with compression seals, while Vermont and Ohio reported being very satisfied with asphalt plug joints. Still others reported positive experiences with other joints and header systems. Agencies that reported positive experiences were contacted and asked to provide samples of their detail sheets for joint repair and replacement work. Just as with the manuals, the detail sheets are unique and vary from owner to owner, but many of them have good details or instructions that are examples of best practices.

Vendors and joint suppliers were asked if they knew of owner agencies that had good specifications or examples of best practices. Only one supplier responded with information on two state agencies, that being Georgia and Virginia. The agencies were contacted and copies of new specifications they have written were obtained.

The team consulted with one contractor who does a significant amount of joint repair and replacement work in the mid-Atlantic region. This contractor provided a wealth of information about contracts, execution of repair and replacement work, and estimating jobs.

As discussed in the literature review section, Dahir and Mellott (1987) reported on a study conducted in the 80's to evaluate the performance of in-service joints in Pennsylvania. The authors developed a scheme for rating the performance of joints that considered seven different performance factors and yielded a final rating on a 5-point scale. The study seemed very relevant to this work. Pennsylvania Department of Transportation was contacted to see if the procedure had ever been used in practice to make decisions about joint replacement. The point of contact, who has many years of experience in bridge operations in Pennsylvania, said that there was no present knowledge of the study and that the procedure had not been adopted by the agency.

Performance Metrics

One objective of the project was to develop performance metrics for small movement bridge joints. In doing this the research team proposed using the AASHTO LRFD Bridge Design Specification as a guide in developing the metrics: the main performance metric categories proposed were serviceability, constructability, and economy, which are design objectives in Section 2 of the LRFD Specifications. Serviceability was broken down into serviceability objectives of the LRFD Specifications: durability, inspectability, maintainability, and rideability. Using this as a starting point, questions were included in the survey to gage stakeholder opinion on how effective a particular performance metric might be, and how easy or difficult it would be to gather the data necessary to evaluate a given metric. The feedback on these proposed performance metrics were presented earlier in this report.

The survey results, which are presented in Figure 14 through Figure 18, provided some insight into which of the proposed performance metrics might be viable options; however, there was no strong agreement among respondents, which is evident by the scatter of results in Figure 14. Therefore, rather than picking just a few specific metrics, the research team proposes a system of performance metrics that is simple and flexible, but also allows for detailed comparisons between different joint systems. It can also be adapted by individual owners for their specific needs.

The proposed performance metrics are:

- Joint opening – the maximum opening of a joint.
- Joint movement – the limit for range of movement of a joint.
- Skew – the limit for range of skew angle the joint can be used and still function properly.
- Expected service life – the length of time a joint can be expected to perform when properly maintained.
- Installed cost – the actual cost of the installed joint, which includes materials, equipment, manpower, maintenance of traffic, and administrative costs. Many of these costs will be state or region specific; material costs, however, are more uniform. Presented in Table 6 Typical

materials costs of joints in use today are typical material costs for various types of joints commonly in use today.

Table 6 Typical materials costs of joints in use today

Type	Seal only ($/ft)	Total System ($/ft) Includes header, seal, hardware	Estimate
APJ	N/A	30	2” deep 20” Mastic = $25.20 /ft. 1.5 lbs /ft adhesive @ $.86 = $1.29 ¼ x 8” plate @ $4.00/ft = $4.00 Total = $30.49/ft
Closed Cell Foam	7	42	3” x 2-1/2" closed cell foam = $ 7.25 / ft. Elastomeric concrete w primer (10”x4”blockout) = $33.40 /ft. Bonding adhesive (2 part epoxy) = $ 1.00 / ft. Total = $41.65
Compression (polychlorprene)	22	56	3” compression seal = $22.00 / ft. Elastomeric concrete w primer (10”x4”blockout) = $33.40 /ft. Bonding adhesive (2 part epoxy) = $ 0.90 / ft. Total = $56.30
Open Cell Foam	32	66	3”pre-formed, pre-compressed, self-expanding, with silicone surface (epoxy adhesive and silicone included) = $32.22 Elastomeric concrete w primer = (10”x4”blockout) = $33.40 Total = $65.62
Preformed “ʌ” and “M”	35	69	3” “ʌ” seal = $35 /ft. Elastomeric concrete w primer = (10”x4”blockout) = $33.40 Adhesive (silicone) = $ 1.00 Total = $ 69.40
Strip Seal	35	114	2” tall rail set in a 3” x 5” blockout Strip seal with seal = $80.00 per ft. Elastomeric concrete w primer = (10”x4”blockout) = $33.40 Lubricant/adhesive = $ 0.90 Total = $114.30 /ft.
Pourable (2-part silicone)	6	46	2 part rapid cure silicone = $5.90 / ft. Elastomeric concrete = $40.00 /ft Total = $ 45.90

*The table lists commonly ordered sizes for each joint type and is not meant for comparison purposes. The header cost is based on costs supplied by one manufacturer and may not represent the cost of the elastomeric concrete supplied by other manufacturers.

- Constructability - is the installation process simple or complex, are there tight tolerances on dimensions and mixing processes, does workmanship of the installation have a big impact on the joint performance, is specialized equipment required.
- Lead Time – refers to how quickly the joint needs to be replaced and are there schedule and delivery constraints that would preclude selecting some joints over others. For example, the lead time on a pre-assembled strip seal joint may be several weeks or months, whereas mobilizing to install a new header and compression seal could be a matter of days. Schedule constraints, therefore, may preclude selecting the strip seal.
- Location/environment – the limits to geographic location and environmental conditions that the joint can be used and still function properly. Principally, this refers to the operating temperature and the weather at the site.
- Traffic – the Average Daily Traffic (ADT) the joint can be exposed to without a significant deterioration in performance
- Durability – taken collectively this refers to the robustness of the joint. For example, how well does it stand up to the pounding of heavy traffic, snow plows, and is frequent maintenance or repair required.

Presented in Table 7 is a matrix with nominal data on these factors for each type of joint. The information in the table has been derived from the survey of stakeholders and experts in the field. In the table “L” refers to “low”, “M” to “Medium,” and “H” to “High.” For Installed Cost, Constructability, Lead Time, Location/Environment, and Durability the ratings are simply a relative comparison. More specifically, for Durability, Low (L) implies a less robust, less durable joint, and High (H) refers to a highly robust and more durable joint. For Constructability, Low (L) implies a joint that is simpler to install, does not require specialized equipment, and does not have tight tolerances; High (H) refers to a joint that is more difficult to install, may have tight tolerances, may require specialized equipment, and a more skilled workforce. For the other factors quantitative values or ranges are specified. Using this as a guide the owner/engineer in charge of the project can make the selection that is best suited for the project.

Table 7 Performance Metrics

	Max Opening (in)	Joint Movement (in)	Skew[1]	Expected Service Life (years)[2]	Installed Cost	Construct-ability	Lead Time	Location/ environment	Traffic[3] (ADT)	Durability
Asphalt Plug Joint	3	<1.5	L-M	7.5	M	H	M	M	L-M	M
Compression seal	4.25	<2.5	L-M	10	M	M	L	M	M	M
Closed-cell Foam	4	<2-3	M	8.9	M	M	L	H	M	L-M
Open-cell foam	4	<4	M-H	8	M	L	M	H	M	M
"ʌ" & "M"	4	<4	M	8	M	L	L	M	M	M
Strip seal	4	<3-4	M	16.0	H	H	H	H	H	H
Pourable joint	3	<1	L-M	7.5	L	L	L	H	M	L
Open/Sliding Plate/Butt joint	3	<2-3	H	23.1	L-H	L-H	L-M	H	M	M

1. Skew: L=0°-15°, M=15°-25°, H>25° (but not unlimited)
2. Based on owner survey responses
3. Traffic (ADT): L=0-15,000; M=15,000-45,000; H>45,000 vehicles per day

Life Cycle Cost (LCC)

Life Cycle Cost came in very highly ranked in the survey as a possible performance metric. Three out of the four stakeholder groups ranked it very high in effectiveness, but also recognized that the data needed to compute LCC was difficult to obtain. As mentioned earlier, based on the survey results and follow-up contacts, not a single owner that responded to the survey indicated they currently use LCC in their evaluation of joint options.

As mentioned in the *Literature Review* section, an extensive study on the performance of joints in the UK was conducted in the 90's and is reported in Barnard and Cuninghame (1997). In their report the authors present a fairly detailed life cycle cost analysis for joint replacement. While the report centers around joints used in the UK, the LCC procedure is applicable to practices in the U.S., if not "as-is", then perhaps with some slight modification. The procedure is described here along with an example of how the LCC would be calculated for a typical replacement project.

Using their procedure, seven different pieces of information are needed to conduct the analysis. These are presented in Table 8:

Table 8 Factors required in the life cycle cost calculation

Data	**Notation**
Material and installation cost of the joint ($)	MIC
Fixed contract cost ($)	FCC
Extra daily contract cost ($/day)	EDCC
Road user delay costs ($/day)	RUDC
Indirect failure costs, to deck, superstructure and substructure ($)	IFC
Installation/contract period (days)	ND
Service life of the joint (years)	SL

These data are needed for each joint type and road classification that is to be included in the analysis. In the Barnard and Cuninghame study the analysis was conducted for 10 different types of joints and four different roadway classifications: single lane road, two lane road, 2 lane highway with an ADT of 40,000 vehicles, and 2 lane highway with an ADT of 60,000 vehicles. For a given design scenario, the Total Replacement Cost (TRC) of the joint is calculated as

$$TRC = MIC + FCC + EDCC * (ND - 1) + RUDC * ND + IFC \quad (1)$$

Once the total replacement cost is determined, the life cycle cost can be calculated two ways. The simplest approach is to calculate the average annual replacement cost

$$\text{Average annual replacement cost} = TRC / SL \quad (2)$$

Alternatively, the life cycle cost (Barnard and Cuninghame referred to this as "whole life cost") can be calculated as the sum of the initial replacement cost plus the discounted future cost. This can be expressed as

$$LCC = TRC * (1 + SDF) \tag{3}$$

in which SDF is the sum of the discount factors of future replacements. The discount factors are calculated as

$$DF = \frac{1}{(1+R)^Y} \tag{4}$$

where R is the discount rate and Y is the replacement year. Barnard and Cuninghame provide tables of the discount factors for an 8% discount rate, and sum of the discount factors for 50 year period.

Presented in Table 9 is an example calculation for two different joint replacement options, an asphalt plug joint and a strip seal, on a multilane highway with an ADT of 40,000 vehicles (note the data used in the example is from the Barnard and Cuninghame study and does not reflect actual or current costs for the U.S., it is presented just for the purpose of illustration).

The procedure is relatively simple and could be easily applied, with perhaps some modification, for joint replacement in the U.S. The challenge of course is gathering the data needed to conduct the analysis. The most difficult data to get a handle on would be the road user delay costs and the indirect failure costs to the deck, superstructure, and substructure. The material, labor, equipment, and contract costs should be obtainable. Finally, as the calculation is of course dependent on service life, having a reasonably accurate estimate of service life would also be important.

Table 9 Example LCC calculation

Cost Category	Asphalt Plug Joint	Strip Seal
MIC ($)	$2400	$15000
FCC ($)	$10000	$10000
ND (days)	4.8	28
EDCC ($/day)	$1000	$1000
RUDC ($/day)	$2400	$2400
IFC ($)	…	…
Emergency Action Only	$200	$200
Pier Concrete Repairs	0	0
Major Deck Repairs	0	0
Total Cost per Replacement	$27,920	$119,400

Whole Life of the bridge (50 years)		
SL (yrs)	5	20
Initial cost of replacement joint ($)	$27920	$119400
Sum of discount factors for subsequent replacements	2.085	0.261
Future costs ($)	$58213.2	$31163.4
Life Cycle Cost ($)	$86,133	$150,563

Average Annual		
Total Cost per Replacement	$27920	$119400
SL (yrs)	5	20
Average Annual Replacement Cost	$5,584	$5,970

In the end, because of a general lack of data, and a procedure for collecting and storing the data, an LCC approach was not included in the proposed guidelines.

Benefit/Cost Ratio (BCR)

An alternative, and much simpler performance measure that can be calculated is the Benefit/Cost Ratio, which is defined as:

$$BCR = \frac{Intended\ Service\ Life\ (years)}{Installed\ Cost\ (\$)} \tag{5}$$

The BCR is similar to LCC but does not account for the indirect costs due to road user delay and indirect failure costs. Note that the numerator in this calculation is the intended service life of the joint (how

many years one hopes to get out of the joint), not the expected service life (the maximum life one can expect to get out of a joint). This can become important, particularly in repair or replacement situations, when for example it is known that a bridge is to be replaced in a few years and only a limited number of years of service are needed. The installed cost includes supplies and materials, manpower, equipment, maintenance of traffic, and administrative costs. All of the costs are, of course, joint dependent and can also vary from state to state, or region to region. However, the data needed to calculate the BCR should be readily available to owners and therefore would be a viable metric to use in comparing different joints. The BCR has been included in the proposed guidelines.

Common Joint Material Tests

A challenge that owners face when selecting a joint or seal replacement is the wide array of different material properties that are reported for the different joint systems. Most of the properties that are reported are determined using ASTM or ISO test standards, or some variation of them. However, even for joints or seals that are similar from one manufacturer to another, the specific properties that are reported and the tests that are used to determine them are not consistent. Manufacturers themselves chose what to test, how to test, and how to report the results. Presented in Table 10 through Table 16 are the material tests performed by the different manufacturers, grouped by type of joint. It shows the wide variation in properties that are reported for different types of seals. While it is beyond the scope of this project, future efforts could be aimed at developing a standard set of material properties and tests for different types of joints. Having a consistent set of material properties for similar joint types would help owners compare different products, and also more easily evaluate new products that are introduced to the market.

Manufacturer Legend:
Chase - Chase
Crafco – Crafco
DS – D.S. Brown
DSA – Dynamic Surface Applications
EMSeal – EMSeal
RJ – R.J. Wastson
Wabo – Watson Bowman Acme

Table 10 Common material tests: Asphalt Plug Joints

Test	Manufacturer			
	Crafco[1]	DSA[3]	Wabo[4]	DS[2]
Asphalt Compatibility	X	X	X	X
Bond, 100 % Elong 3 cycles at -7°C (+20°F)			X	
Bond, 50% extension, 25mm, 3 cycles	X			X
Brookfield Viscosity, 400°F (204°C)	X			X
Ductility, 25°C (77oF), min.	X	X	X	X
Flexibility	X			X
Flexibility/Pliability @ -10°F		X	X	
Flow 60°C (140oF), 5 hr., max.	X	X	X	X
Low Temperature Penetration -18°C (0oF) 200g, 60s, min.	X	X	X	X
Maximum Heating Temperature	X			X
Non-Immersed Bond @ 20°F,		X		
Penetration @ 77°F (25°C) 150g,5 s	X	X	X	X
Recommended Application Temperature	X	X	X	X
Resiliency, 25oC (77oF)	X	X	X	X
Safe Heating Temperature		X	X	
Softening Point, min.	X	X	X	X
Tensile Adhesion @ 77°F	X	X	X	X
Unit Weight at 60°F (15°C)	X			X
VOC	X			

1- http://www.crafco.com/PDF%20Files/Matrix%20502/Matrix_502%20PDS.pdf

2- http://www.dsbrown.com/Resources/Bridges/Matrix/B_EJS_Matrix%20502_DATA_v002.pdf

3- http://www.dsa-ltd.com/sites/default/files/Thorma-Joint_Specification.pdf

4- https://wbacorp.com/products/bridge-highway/armorless-joint-systems/wabo-expandex/

Table 11 Common material tests: Closed cell foam

Test	Manufacturer		
	Chase[1]	RJ[2]	Wabo[3]
Compression Deflection 25%	X		
Compression Recovery (% of original width) 22 hr @ 73 o F (23 o C) ½ hr recovery			X
Compression Set: 50% compression for 22 hours @ 73 o F (23 o C) 24 hour recovery	X	X	X
Compression Set: 50% compression for 22 hours @ 73o F (23 o C) 2 hr recovery	X	X	X
Compressive Strength		X	
Density	X	X	X
Elongation	X	X	X
Extrusion (specimen compressed 60% of original thickness with 3 restrained sides)			X
Recovery	X		
Tear Resistance	X	X	X
Tensile Strength	X	X	X
Thermal Stability	X		
Water Absorption	X	X	X
Weatherability	X	X	X

1- http://chasecorp.com/products/ceva-products/metazeal-s/

2- http://www.rjwatson.com/wp-content/uploads/zed-seal-data-sheet.pdf

3- https://wbacorp.com/products/bridge-highway/armorless-joint-systems/wabo-crete-flex-foam

Table 12 Common material tests: “M” and “∧” seals

Test	Manufacturer	
	DS[1]	RJ[2]
Compression Set At 212° F 70 hrs.		X
Durometer Content	X	X
Elongation	X	X
Operating Temperature Range		
Ozone Resistance	X	
Tear Strength	X	X
Tensile Strength	X	X
Water Resistance	X	

1- http://www.dsbrown.com/Resources/Bridges/VSeal/B_EJS_V-Seal%20ExpanJointSyst_DATA_v007.pdf

2- http://www.rjwatson.com/expansion-joints/silicoflex-joint-sealing-system/

Table 13 Common material tests: Elastomeric cellular compression seals

Test	Manufacturer		
	Wabo[3]	DS[1]	RJ[2]
Adhesion Properties			X
Brittle Point, °F			X
Compress Strength: 5% deflection			X
Compress Strength: Resilience			X
Compression Set 168 hrs @212°F			X
Compression Set 168 hrs @73°F			X
Compression-Deflection Properties: LC Max., in (mm)		X	
Compression-Deflection Properties: LC Min., in (mm)		X	
Compression-Deflection Properties: Movement Range, in (mm)		X	
Elongation at Break, min	X	X	X
Hardness, Shore A	X	X	X
Heat Aging 70 hours @212ºF (100ºC): Elongation, Max. % decrease	X	X	
Heat Aging 70 hours @212ºF (100ºC): Hardness, Max. change	X	X	
Heat Aging 70 hours @212ºF (100ºC): Tensile Strength, Max. % decrease	X	X	
Low Temperature Recovery: 22 hrs -20°F, min	X	X	
Low Temperature Recovery: 70 hrs 212°F, min	X	X	
Low Temperature Recovery: 72 hrs 14°F, min	X	X	
Oil Swell, 70 hrs. @ 212ºF(100ºC): Weight Change, max	X	X	
Ozone Resistance, 70 hrs. @ 104ºF(40ºC)	X	X	X
Tear Strength lb/in			X
Tensile Strength, min	X	X	X
U.V. Resistance			X
Water Absorption			X

1- http://www.dsbrown.com/Resources/Bridges/Delastic/B_DPCS_CharPropCVandCA_SPEC_v012.pdf

2- http://www.rjwatson.com/wp-content/uploads/type-me-seal-data-sheet.pdf

3- https://wbacorp.com/products/bridge-highway/joint-seals/wabo-compressionseal-bridge-series/

Table 14 Common material tests: Open Cell Foams

Test	Manufacturer
	EMSEAL[1]
Foam	
Impregnation	X
Temperature Service Range: -40°F to 185°F	X
UV Resistance (Accelerated Weatherometer)	X
Resistance to Aging	X
Bleeding: -40°F to 180°F (-40°C to 85°C)	X
Compression Set	X
Silicone Coating	
Percent Solids (minimum)	X
Specific Gravity	X
Following tests conducted on Sealant Cured after 21 days at 25°C (77°F) and 50% RH:	
Elongation Percent Minimum	X
Joint Modulus at 50 percent Elongation, psi (kPa) maximum	X
Joint Modulus at 100 percent Elongation, psi (kPa) maximum	X
Joint Modulus at 150 percent Elongation, psi (kPa) maximum	X
Adhesion to Concrete, minimum percent Elongation	X
Adhesion to Asphalt, minimum percent Elongation	X
Joint Movement Capability, +100/-50 Percent, 10 Cycles	X
Weatherability	X
Flexibility	X

1- http://www.emseal.com/Products/Infrastructure/BridgeJointSeals/EMSEAL_BEJS_TD_Xw.pdf

Table 15 Common material tests: Strip Seal

Test	Manufacturer	
	DS[1]	**Wabo[2]**
Tensile Strength, Min., psi (Mpa)	X	X
Elongation at break, Min.	X	X
Hardness, Durometer A	X	X
Ozone Resistance, 20% elongation, 300 pphm 104ºF (40ºC) (70 hrs.). Wipe surfaces with solvent to remove contamination.	X	X
Heat Aging 70 hours @212ºF (100ºC): Tensile Strength, Max. % decrease	X	X
Heat Aging 70 hours @212ºF (100ºC): Elongation, Max. % decrease	X	X
Heat Aging 70 hours @212ºF (100ºC): Hardness, Max. change	X	X
Oil Swell, ASTM Oil #3,70 hours @212ºF (100ºC). Max weight increase.	X	X
Compression Set, 70 hours,@212ºF (100ºC)	X	
Low Temperature	X	
Low Temperature Stiffening. 7 Days @ +14ºF (-10ºC), Hardness Type A Durometer: Points Change	X	X

1- http://www.dsbrown.com/Resources/Bridges/Steelflex/B_EJS_SteelflexStripSealExpansionJointSystems_SPEC_V004.pdf

2- https://wbacorp.com/public/userfiles/WaboStripSeal_0613_DataSheet.pdf

Table 16 Common material tests: Pourable seals

Test	Manufacturer		
	RJ[2]	Wabo[3]	DS[1]
Cure evaluation		X	
Hardness (Shore A)	X	X	X
Heat Aging	X		X
Joint elongation		X	
Joint Modulus, 100%		X	
Leveling		X	
Low Temperature Flexibility (@ -40°F)	X		X
Movement Capability	X		X
Pot Life	X		X
Recovery- Bond Durability Test Blocked @ 50% for 48 hours	X		X
Shelf Life @ 70º F (In sealed container)	X		X
Specific Gravity		X	
Stress @ 150%		X	
Tack free time		X	
Tensile Strength	X		X
Ultimate Elongation	X	X	X
Water Immersion	X		X

1- http://www.dsbrown.com/Resources/Bridges/DelasticLS/B_EJS_Delastic%20LS%20Pourable%20Bridge%20Seal_DATA_v004.pdf

2- http://www.rjwatson.com/wp-content/uploads/ura-tron_data_sheet.pdf

3- https://wbacorp.com/public/userfiles/WaboCrete_SiliconeSeal_1010.pdf

Compression Set Investigation

“Compression set” describes the permanent deformation that remains in a material after an applied stress is removed. It is typically quantified as the percent of the original thickness lost after the stress is removed. Due to their relatively low Young’s modulus, Closed Cell Foams (CCF) are particularly susceptible to compression set.

When used in a small movement bridge joint, if CCF experiences compression set as a result of the joint being closed for a period of time it can induce high tensile stress in the bond line and the material as the joint opens back up in colder temperatures. Manufacturers of CCFs typically report an acceptable extension of 20-30% in tension, however, failure in the bond and tearing of the foam has been reported (Table 4, Figure 19). This has caused some owners to discontinue the use of CCF’s, or limit the materials to be in compression only (Figure 10 and Figure 11 of the survey results show the limited use and level of satisfaction with CCFs).

Figure 19 Compression set in parapet joint seal

Most manufacturers will report the compression set values of their material that the designer can consider while selecting a joint type and determining its size. The most commonly referenced standard for measuring compression set in a foam is ASTM D3575, which requires a 22-hour compression cycle at an air temperature of 73° F. As the seasonal compression cycles these materials experience in service are on the order of months, it is immediately apparent that this test procedure may not be appropriate for the bridge application, as the cycle required by ASTM D3575 is only a small fraction of what the material will actually experience in a bridge joint. In addition, regions of the country experience 20° to 30° warmer average daily temperatures during summer months than the recommended testing temperature of 73° F. For these reasons, the appropriateness of the standard, for measuring compression set in foams used in bridge joints, has come into question.

The primary objective of this task sub-investigation was to investigate the effect of compression set on CCFs, and evaluate the accuracy of the current ASTM standard as it applies to the compression set experienced by in-service CCFs used in bridge joints. By conducting a series of tests performed in accordance with the current ASTM, alongside parallel tests conducted at elevated temperatures and for longer compression cycles, a comparison was made to observe the validity of the ASTM standard. A follow-up study was then conducted on the same samples to measure their final thickness (and therefore their compression set) long after the recommended 24-hour rebound period. This was in an effort to evaluate the rebound period suggested by the ASTM standard, which is also far shorter than what bridge joints experience while in service.

Another series of tests that were conducted involved performing tensile capacity tests on bonded samples that have experienced a compression cycle, in order to simulate the tension that a CCF joint will experience in the colder months due to the contraction of the bridge deck. These tests were performed to determine the tensile capacity of the foam as well as the strength of the bond, in order to better understand the repercussions of compression set. If the foam or bond were to fail when the foam section was still near its original thickness, or within the prescribed tensile limits (usually 20-30% of the original thickness), it would suggest that the effects of compression set are making a significant contribution to the failure of these foams. If neither the foam nor adhesive fail until the extension of the foam has far surpassed its original thickness, this would suggest that the existence of compression set in a foam member may not be significantly affecting its tensile capacity at all. This test will be the final step in better understanding the effects of compression set on CCFs, and the validity of the current testing standards that govern their behavior.

Compression Testing

In this phase of the work a series of experiments were conducted to evaluate the suitability of the ASTM D3575 standard as it applies to CCF bridge joints, by modifying the temperature and compression cycle duration of the test and comparing the results with those obtained using the standard procedure. The length of the rebound duration, which is also specified in the standard, was also studied. The experiments were conducted using CCFs from four different suppliers: Watson Bowman Acme, Chase, Polyset, and R J Watson.

Test Set-Up and Procedure

Foam specimens were prepared in accordance with the ASTM standard. It requires a minimum of three replicates be tested per material. Specimens are required to have a cross section of 2” by 2”, and a thickness of 1”. Assuming that the material is isotropic, the CCF was ordered in 2” by 2” by 36” rolls and cut into 1” slices using a horizontal band saw.

The fixture used to compress the specimens is described in the standard as two steel or aluminum plates held together by bolts or clamps; the specimen compressed thickness is controlled by spacers. To accommodate 12 specimens per apparatus (4 suppliers by 3 replicates), two 12” by 12” by 3/8” aluminum plates were used. The dimension of the plates was controlled by the standard’s requirement

that the compressed specimens must not come into contact with each other at any point during the compression cycle. The 12" by 12" plates were sufficient to accommodate this requirement. The plates were held compressed by bolts in each corner.

The procedure for measuring each specimen was performed as described in the standard. To ensure repeatability in addition to precision, the standard requires the use of a dial gauge with a minimum foot area of 1 in^2, and maximum pressure of 0.035 psi (so as to not cause significant deformation of the foam while making the measurement). The thickness of the specimen is calculated as the average of five measurements: at the center, and at each of the four corners of the specimen. A stable mounting station was used to support the dial gauge using an adjustable arm and a magnetic base. The dial gauge was calibrated using precisely cut ½" cubes of key stock that were also used as spacers for the compression fixture. Once the average original thickness of each specimen was calculated and recorded, the compression cycling could begin.

The bottom plate of each compression fixture was marked to indicate the exact placement of each specimen in accordance with the design shown in Figure 20. Once all 12 specimens for a given trial were in place, the top plate was positioned on top, the ½" key stock spacers were placed in each corner, the plates were compressed and secured with the bolts.

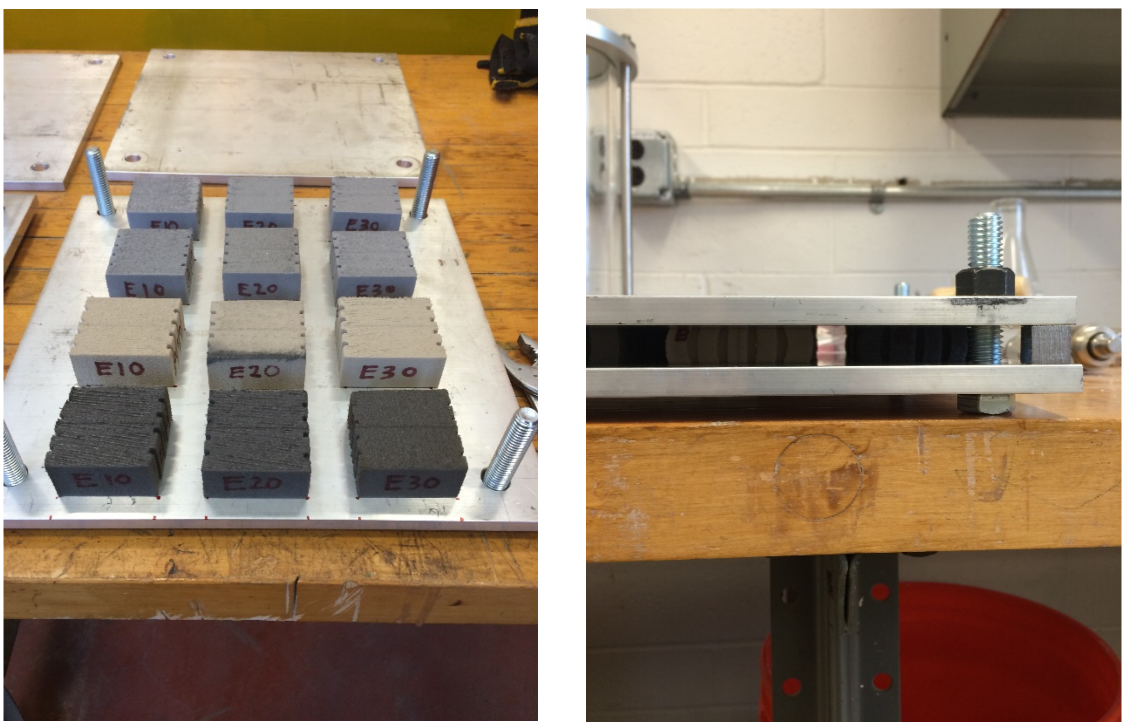


Figure 20 Specimens loaded in open apparatus (left); specimens compressed to 0.5 inches (right)

Four different sets of specimens were tested, each for a different compression cycle duration. The first trial used the 22-hour compression cycle required by the ASTM standard; the other sets were held for

compression cycles of 1, 2, and 3 months, respectively. These sets were maintained at an ambient temperature of 73°. To study the effect of elevated temperature on compression set the tests were repeated on new specimens, which were held at a temperature of 110°F for the duration of the compression cycle.

The elevated temperature was determined by investigating the average daily temperature of Phoenix, Arizona (the city with the warmest recorded summers in the U.S.), between the months of June and August. By analyzing the temperature data presented on WeatherSpark's website (www.weatherspark.com), the average daily temperature remains around 105° F during these months, reaching just under 110° F at its 90th percentile. The value of 110° F was therefore selected as a worst case, but realistic condition.

At the end of the compression cycle the fixture was released by unscrewing the nuts and removing the top plate. The specimens remained on the bottom plate, untouched for a rebound period of 24 hours as prescribed by ASTM D3575. At the end of the rebound period the thickness of each specimen was measured using the same procedure as before. Using the five point averages recorded from the original and final thicknesses, the compression set for each specimen was calculated as:

$$C_d = \frac{\left(t_o - t_f\right)}{t_o} x100 \tag{6}$$

where t_o is the original thickness, t_f is the final thickness, and C_d is the compression set. The values for the three replicates of each supplier were then averaged, to produce a single compression set value for the material of each supplier.

The follow-up study on rebound duration, prompted by the analysis of the compression test data, did not require any physical experimentation, only a continuation of the final thickness measurements that had been taken at the conclusion of each compression cycle. The tested specimens that were to be remeasured were stored at room temperature and allowed to rebound freely, as directed by the ASTM standard. The same apparatus and procedure was used to measure the thickness of the specimens. Because these were the same specimens that were prepared and tested in accordance with ASTM D3575, allowing them to continue to rebound freely at room temperature ensured that the only modification being made was to rebound duration.

During the compression tests, the compression cycle duration was modified from 22 hours to be on the order of months. In selecting the rebound duration it was logical to make a similar modification and analyze a rebound duration on the order of months as well. It was decided that measurements were to be taken once a week over the course of a 3 month period, to match the maximum compression cycle duration. The new final thickness of each specimen could then be averaged over the three replicates of each supplier, and a new single compression set value calculated using the equation from the standard. The compression set for each supplier computed once each week were plotted against time to investigate the effect of rebound duration on compression set.

Results and Discussion

The final compression set values for the CCFs from each supplier are presented in Table 17. Once again, each value represents the average of the three specimen replicates. This table includes the results for the standard 22-hour test, alongside the results of the modified compression cycle duration tests. Results are shown for the ambient temperature (73°F) and for the elevated temperature (110°F). The different materials are simply listed as “A”, “B”, “C”, and “D”, and not by manufacturer, as the goal here was not to compare one manufacturer’s product against another’s.

Table 17 Compression set expressed as percent loss in original thickness

	73°F				110°F			
Supplier	22 Hr	1 Month	2 Months	3 Months	22 Hr	1 Month	2 Months	3 Months
A	12.9	22.9	25.3	28.1	39.7	42.4	43.5	44.2
B	12.1	22.2	25.7	27.7	39.8	41.1	42.9	45.4
C	11.9	28.4	32.6	34.6	47.0	45.5	47.2	48.3
D	11.1	23.5	27.5	30.4	46.1	46.6	49.8	49.0

The specimens that were tested at room temperature with a 22-hour compression cycle represent the original testing method prescribed in the standard, and as such can be compared with the values reported by the suppliers. It is important to note that the make-up of the 4 materials tested is very consistent, and that there is not a large amount of variability between the individual manufacturers. According to the data sheets for these materials, the reported compression set for their products lie in the 9-10% range. As seen in Table 17, the compression set measured in this investigation was just slightly greater, in the 11-13% range. The small difference between these two sets of data can likely be attributed to variations in the measuring process, such as a difference in the pressure inherent in the dial gauges, or perhaps material batch variability. Though slightly greater, these compressions set values validate the quality of the procedure conducted in this study, as the results are close to those reported by the suppliers.

Comparing the room temperature 22-hour values with the elevated temperature results reveals an approximately 300% increase in compression set as a result of the increased temperature alone. By comparing elevated and room temperature data for any compression cycle, it is clear that temperature has a significant effect on the compression set. As temperatures are unlikely to remain near the 73° F mark when these joint seals are compressed to their maximum in the field, this prescribed temperature may not be appropriate for evaluating the performance of this material in all regions of the country.

Presented in Figure 21 are graphs of compression set-versus-compression cycle duration, for the ambient and elevated temperatures. Considering the elevated temperature trials first (Figure 21 (right)), it can be seen that while very gradual, there is a general increase in compression set as the cycle duration increases. The correlation between compression set and cycle duration is likely being masked by the extreme effects of the elevated temperature. In spite of these effects, the values still exhibit a

slight linear increase in compression set with cycle duration. A more indicative portrayal of the effects of compression cycle duration is found in the room temperature trials (Figure 21 (left)). When the compression cycle was increased from the standard 22-hours to the shortest of the new experimental cycles, the 1 month trial, all materials experienced a 100% increase in compression set. The compression set increases further with increasing cycle duration, but the most significant change is between 22 hours and 1 month. It is clear from these results that the duration of the compression cycle has a significant effect on the final compression set, with up to a 150% increase in compression set between the current standard and longest cycle. As the longer cycles are more reflective of the in-service conditions of bridge joints, the significant difference between these results and the testing standard suggest that a more appropriate compression cycle duration could be selected for this test to increase its accuracy for these types of materials.

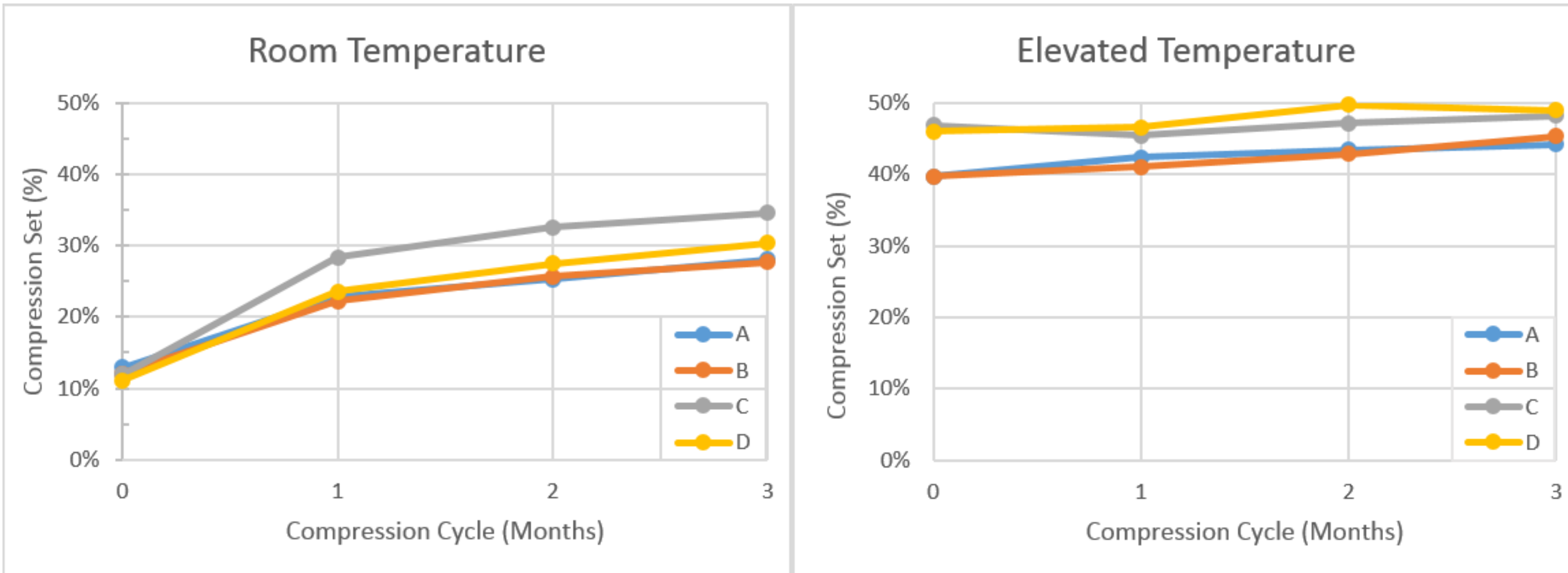
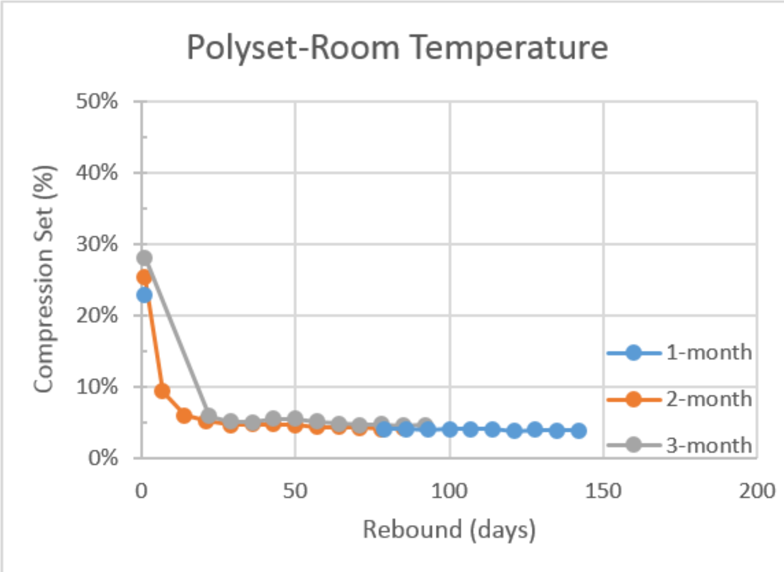


Figure 21 Compression set for room temperature trials (left); compression set for elevated temperature trials (right)



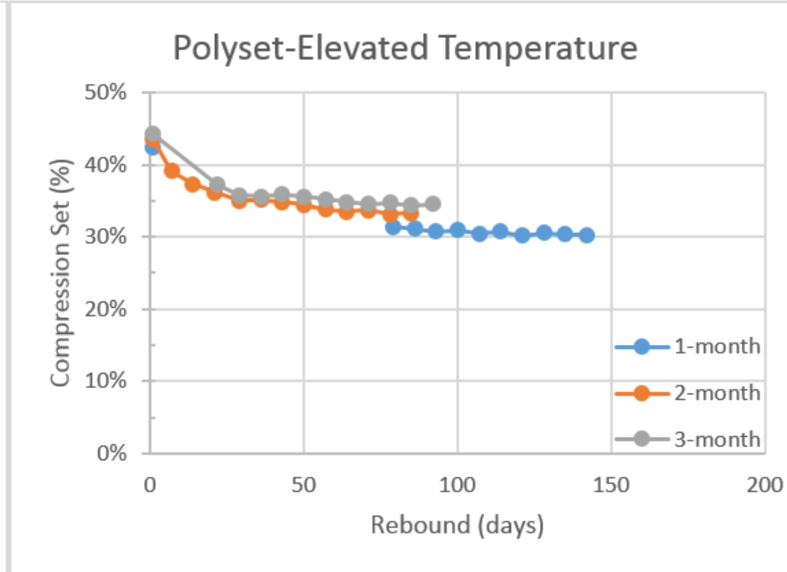


Figure 22 Compression set data for extended rebound durations

For both temperature and cycle duration, it is apparent that the current ASTM D3575 testing standard may not be an appropriate compression set test for all CCF's in all regions of the country. The significant difference between the results obtained using the current standard procedure and the modified procedure, which better simulates the in-service conditions of bridge joints, shows that several changes to the standard as it applies to CCF bridge joints are warranted. Modifications to the compression cycle for these types of materials would increase its accuracy, as would a testing temperature that varied based on service region. In the absence of these modifications, and in order to avoid instances of tensile stress in the joint gland caused by this lack of rebound, it may benefit designers to be more conservative when selecting the size of the gland material (i.e., by prohibiting or allowing less tension in the foam by selecting a wider foam), as the results of this study show that the compression set data reported by the suppliers may not always be accurate for every situation.

Presented in Figure 22 is the compression set calculated with the final thickness measurements collected during the extended rebound duration test. The x-axis represents the rebound duration in days, or the amount of time between the completion of the compression test and the measurement of the specimen thickness. These graphs display data for room and elevated temperature specimens, but only for the product of one supplier, which is presented as a typical example of the results of this study. Just as in the compression set study, the differences between the supplier's foam products was not significant in general.

The gap that appears between 0 and 75 days of rebound in the 1-month series is a result of the way in which this part of the study began. Because the decision to perform this work was made after the conclusion and analysis of the compression experiments, some specimens had already been rebounding freely for a much longer time than others. In the case of the 1-month trial, these samples had been released over 2 months before the decision was to continue the rebound measurements, resulting in the gap present in the above graphs. As will be explained later, the data from this study showed that the most significant portion of these trends came after long periods of rebound, so these gaps near the beginning of some of these tests were not considered to be a hindrance to the findings of this study.

The most apparent and important finding of this study is that regardless of the supplier, compression cycle, or testing temperature, closed cell foam will continue to rebound after the first 24-hour period. Comparing the y-intercepts of these graphs (which represent the compression set calculated after a 24 hour rebound period) with the compression set calculated at any amount of additional rebound time, shows a significant reduction in the amount of retained compression set. The trends of the individual series in Figure 22, and the rate of decrease in compression set is also a point of interest. Focusing first on the room temperature graph, all specimens experience a significant decrease in compression set, followed immediately by a horizontal asymptote that remains fairly constant over the remainder of the rebound period. For all compression cycles, it appears that approximately 1 month of rebound will result in compression set values in the 4-5% range, which are then unaffected by continued rebounding. This horizontal asymptote reveals a few details about the nature of CCFs. First, all foams stop rebounding at a compression set value that is about half of what is reported by manufacturers (which usually lies in the 9-10% range), undoubtedly due to the brief rebound period prescribed by the current standard. Also,

while the series for the 1-month compression cycle is incomplete, it does offer insight into the behavior of this foam at an extreme rebound duration. Yielding a fairly constant amount of compression set after almost 5 months of rebound strongly suggests that closed cell foams experience permanent losses in thickness, and will never completely return to their original dimensions. Lastly, while the value of each asymptote is very similar for each compression cycle duration, there is a small difference that suggests a relationship between compression cycle duration and permanent compression set. The value of the asymptote is slightly less for specimens that experienced shorter compression cycles. Though only a slight correlation, this agrees with the notion that the longer foam is compressed, the more compression set it will retain.

The results for the elevated temperature specimens bear many similarities, but with some key differences. These graphs also exhibit a period of decay followed by a horizontal asymptote, but the magnitude of decay is much less than the room temperature specimens. This is likely due to the effect of elevated temperature observed in the compression tests, where temperature has such a large effect on compression set that the influence of time (rebound duration in this case, and not compression cycle duration), is much less significant. This effect can also be seen in the magnitude of the asymptote, which levels off in all cases between 30-35%. These values of compression set are higher than all values calculated for the room temperature specimens, including the 24 hour rebound values, and especially the asymptote values of 4-5%. As with the room temperature specimens, the horizontal asymptote is reached after about 1 month of rebound, but the asymptote itself is not quite as stable. Lastly, the same correlation between compression cycle duration and compression set retention exists in the elevated samples (longer cycles retain more compression set), but the difference between the individual series is much greater. This can be noted by visual inspection, where the asymptotes on the elevated graph have distinctly different values, where the series on the room temperature graph are almost completely overlapping. This may also be due to the higher total levels of compression set, and yields even stronger evidence that compression cycle does have a significant effect on compression set retention.

The objective of this Task 4 sub-investigation was to investigate the appropriateness of the 24-hour rebound period prescribed by the current ASTM standard for the testing of compression set in CCFs. Just as with compression cycle, a testing procedure occurring on the order of hours seemed unrepresentative of the conditions these foams experience while in service, which take place on the order of months. The results of this study show that for all varieties of foam product, compression cycle, and testing temperature, the specimens will continue to rebound a significant amount outside the prescribed 24-hour window. Comparing these results with the current standard yields different findings based on the temperature of the compression test. For the room temperature specimens, after about 1 month of additional rebound, the specimens reach a true compression set of about 5%, which is only half of the typically reported values by CCF manufacturers. This means that compared to the more realistic compression cycles and rebound periods experienced during these investigations, the current testing standard may be over-reporting levels of compression set. For the elevated temperature tests, the reduction in compression set retention was not as significant. Similar to the room temperature specimens, a true compression was reached after about 1 month of rebound, but this value remained

between 30-35% for all compression cycles. This data showed much higher levels of compression set retention in the elevated temperature samples, and a slower decrease in compression set over time. These results from the rebound tests confirm the suggestion from the compression tests that testing temperature has the greatest effect on compression set. Also, at a minimum of 30% compression set, these values are still 3 times greater than the average reported value using the current standard. Though increased rebound durations do reduce compression set retention in elevated specimens, the current standard under-reports compression set values by a factor of 3. By under-reporting the values of elevated specimens and over-reporting the values of room temperature specimens, the 24 hour rebound period of the current standard was shown to be inappropriate for both testing temperatures.

Tension Testing

Bridge owners from various state agencies have reported failures of CCF joints; speculation is that this is due to tearing in tension. As a result, some agencies have limited their use of CCFs to exclude situations where tension is likely to occur. However, most manufacturers report tensile capacity on the order of 20-30% of their original thickness. Clearly there is a disconnect between the suppliers and bridge owners when it comes to the expected performance of these foams in tension. Since compression set has been shown to be a poorly understood and an inaccurately reported phenomenon, it is possible that it is the cause of the less than expected performance of CCFs in tension.

In this phase of the work, a series of experiments were designed to determine if compression set is contributing to the failure of foams in tension. This was accomplished by simulating the conditions experienced in service by the foam. To do this, CCF samples were first bonded between steel plates using the manufacturer’s adhesive, then compressed and held for a specified duration and at a specified temperature. At the end of the compression cycle the specimens were released and immediately placed in a universal testing machine and tested in tension to failure. The key questions to be answered by these tests are: (1) can the foam carry tension, and if so, how much, and (2) what is the mode of failure? If the tensile capacity of both the foam and the bond are high enough to prevent tearing of the specimen in tension after experiencing a compression cycle, it is likely that other factors are affecting the tensile behavior. If the specimens do tear after experiencing a compression cycle, this would suggest that compression set may be a contributing factor to the failure of CCFs.

Test Set-Up and Procedure

In this series of tests individual specimens were bonded between steel plates using the manufacturer’s adhesive system. Care was taken to follow each manufacturer’s specific instructions to ensure a high quality bond. The specimens were then compressed and held at a specified temperature and for a specified duration. Upon completion of the compression cycle the specimens were released and immediately placed in a tensile testing machine and loaded in tension to failure. The maximum load, elongation, and mode of failure were recorded. The same CCF’s materials that were used in the compression tests were used in the bonded tension tests.

The compression-tension fixtures for these tests were designed to handle a single specimen at a time (as opposed to multiple specimens like in the compression tests). The fixture consisted of two 6"x6"x1/4" steel plates with holes at each corner. Bolts in each corner were used to hold the plates together during the compression cycle. The dimensions of the plates were selected to ensure that the expanded specimen would not come into contact with the bolts when compressed.

CCF's used in bridge joints are bonded to the header. To enhance the bond the foam is manufactured with grooves cut into two opposing sides. In these tests, to maintain the 2"x2" compressed cross-section and allow for a strong bond, the specimens were cut into 2"x2"x2" cubes.

The adhesive and the steel plates were prepared in accordance with the manufacturer's procedures. The steel plates were first ground to a bright white finish. A 1 mm thick layer of epoxy was then applied to both of the steel plates, and to both of the grooved sides of the foam. The coated side of the foam was then placed onto one of the coated plates, and the other plate was placed on top. Bolts were passed through the holes, tightened to achieve the desired compressed thickness (1"), and secured with nuts. Spacers placed between the plates were again used to set the compressed thickness. The final step in preparing the specimens in accordance with the supplier's procedure is to clean the foam of any excess adhesive. The procedure does not explain why this is important, but some of the findings of this study demonstrate why excess epoxy can be detrimental to the integrity of the foam in tension, as will be described later. Once this step was completed, the specimens were prepared for the compression cycle portion of testing.

As before, half of the specimens were compressed and held at a temperature of 73^{o}F, and the other half were held at the elevated temperature of 110^{o}F. Two compression cycle durations were imposed in these tests, 22 hours and 1 month. Three replicates of each foam were tested. Once the compression cycle was finished the specimens were immediately subjected to a tensile cycle.

Specimens were tested in a Lloyd T50K Testing Machine, in displacement control. Special loading fixtures were fabricated to connect the specimens to the test machine cross-heads. The displacement rate of the machine was set at the slowest possible rate, 2 mm/min (4.72 in/hour).

The specimen was first loaded into the machine in between the two fixtures, and the crossheads were lowered to hold the specimen in place, to ensure that the specimen would not rebound while the experiment was prepared. Bolts were used to secure the plates to the loading fixture. The load and cross-head displacement were zeroed before the start of each test. Load and cross-head displacement were recorded once every minute during the test. All specimens were tested to failure, i.e., complete separation of the steel plates. Figure 23 shows a typical specimen during testing.

Figure 23 Typical foam specimen extension during tension testing

Results and Discussion

Table 18 Ultimate elongation expressed as percent of original 2” thickness

	73°F		110°F	
Supplier	1 Day	1 Month	1 Day	1 Month
A	82.4	93.9	72.6	84.1
B	79.0	92.8	83.8	94.2
C	110.2	82.3	83.4	78.3
D	69.4	84.1	92.0	78.0
Average	85.2	88.3	82.9	83.6

As foam suppliers usually report allowable tension as a percent elongation, this was the most important data collected from the tensile tests in this study, and is presented for each supplier, compression cycle, and testing temperature in Table 18. Percent elongation is calculated as exactly as defined in equation (6), i.e., the difference between the original and final thicknesses, divided by the original thickness, expressed as a percentage.

Comparing the values obtained with the values typically reported by suppliers (20-30% elongation in tension) immediately shows that foams that were subjected to a compression cycle, therefore experiencing compression set, exceeded their reported values. Though the values differ from supplier to supplier, none of the maximum elongations falls below 69%, and the averages for all compression cycles and temperatures lie between 80 and 90%. This demonstrates clearly that the foam samples performed favorably in tension, even after experiencing compression set. An increase in testing temperature did reduce the maximum elongation, on average, for both compression cycle durations, but only slightly. This agrees with trends demonstrated in all other tests that show elevated temperature having a negative influence on the performance of CCFs. However, this decrease in maximum elongation is so

slight that it is unlikely that an increase in compression set due to increased temperature causes any significant reduction in tensile capacity. Based on the earlier tests, all of these specimens should have experienced some level of compression set before being loaded in tension; however, it does not appear to have affected the tensile capacity of the foam in any way.

Three distinct modes of failure were observed in the tests, as shown in the Figure 24. The first of these can be described as a bond failure. Under high tensile load, this failure occurs when the tensile strength of the adhesive bond is weaker than the foam, causing the foam to separate cleanly from one of the steel plates. In this case, none of the foam is torn in any way. This was the dominate mode of failure of specimens that were compressed for 1 day at room temperature (the 1-day, 73°F data shown in Table 18). Under those conditions it is reasonable to believe that the adhesive, although hardened, had not yet reached its maximum strength, causing the bond to fail before the foam. This failure mode did not occur at all in tests at elevated temperatures, or with longer compression cycles, which supports the idea that the adhesive is weakest in its first day of service. Note, according the suppliers of this foam the epoxy should be cured and ready for use after only 30 minutes.

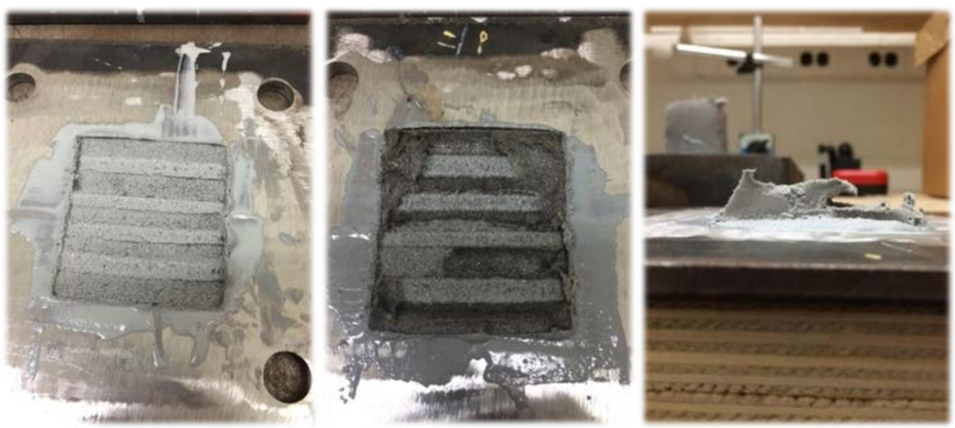


Figure 24 Bond Failure (left); Foam Groove Failure (center); Foam Body Failure (right)

The second failure mode can be described as a foam groove failure: the foam itself tears and is the cause of failure, but this only occurs through the grooves at the edge of the foam sample. As the specimen is put into tension, the grooves that are designed to increase the amount of surface area available for bonding to occur inevitably open up. The thin slices of foam in between the grooves act as ideal failure planes, as they are only a small portion of the thickness of the main body of the foam. The epoxy in this case was strong enough to maintain the connection between the steel and the foam throughout the entire test. This type of failure occurred in the vast majority of tests, including 1 day elevated temperature tests, and most of the 1 month tests. This first shows that the epoxy has gained strength over time, for in many of the 1 day tests, the bond failed first. Secondly, it shows that elevated temperature strengthens the epoxy as well, which performed better than the 1 day tests at room temperature. This is interesting as it appears to improve the quality of the bond, while in the compression tests, elevated temperature seemed to be detrimental as it increased the amount of

compression set present in the foam. Since analyzing the performance of the joint must include both the bond and the foam, these opposing trends are significant when investigating the performance of a joint at elevated temperatures. The foam may experience higher levels of compression set, but the bond usually increases in strength.

The third and final type of bond failure is a foam body failure. Unlike a groove failure, the tear initiates in the interior body of the foam and not in the grooves. This failure was very rare, and only occurred in a handful of specimens. It occurs in the middle stages of tensile testing, when the foam has been stretched past its original length of 2", but before any extreme extension has been reached. In this situation, there is not enough tension present to open up the grooves on the outside of the foam, so there is no obvious failure plane at the edges yet. At this point, if there are any other discontinuities in the body of the foam, that is where tearing will originate. The necessary presence of other significant discontinuities in the foam is the reason this failure mode is a rare occurrence. The only discontinuity significant enough to cause this type of failure was due to excess epoxy that dried on one of the side faces of the foam sample. When excess epoxy dries and hardens on a side face, it constrains the movement of that section of foam. Unable to extend naturally, a stress concentration develops that would not exist if free movement were allowed. These stresses inevitably cause a small tear in the foam, which becomes the new failure plane, and propagates before the grooves can be opened. This shows why excess epoxy must be removed from the exposed surfaces of the foam, as mentioned earlier in describing the bonding process (in a typical bridge joint application removing any excess adhesive from the top and bottom surfaces of the foam is critically important). In a more general sense, this failure is an instructive example of why the quality of the installation is paramount to the long term performance of the seal, and it is important to carefully follow the manufacturer's guidelines on how to install the seal.

Conclusions

The bridge joint seal product known as closed cell foam has fallen out of favor with some bridge owners due to their poor performance in tension (Table 4, Figure 10, Figure 11). Though the suppliers who market these products advertise an acceptable movement range in tension of 20-30%, some bridge owners have moved away from using these products in environments where any amount of tension is expected. This clear disconnect between projected and actual performance suggests that something is affecting these materials in the field that does not exist during production and testing by the manufacturers. Due to its frequent appearance in elastomeric materials such as CCFs, compression set was suspected to be the cause of these tensile failures. This suspicion is compounded by the state of the current ASTM standard used to measure compression set, which prescribes a set of testing conditions that are largely different from the conditions these foams are likely to experience in service, in bridge joints.

This task sub-investigation conducted a variety of experiments in order to evaluate the appropriateness of the current ASTM standard for predicting compression set in bridge deck foam joints, investigate the

performance of CCFs in tension, and determine if compression set is contributing to the frequently reported tensile failures. The results of these tests are summarized below:

- Compression set in CCF's is dependent on compression cycle duration, temperature, and rebound duration. The values of compression set reported, when tested in accordance with ASTM D3575, are not necessarily appropriate for bridge joint applications. Compression set should be measured by testing under conditions that are more reflective of the actual conditions the materials will experience in-service, when used in a bridge joint.
- For specimens held at ambient temperature, compression set increases with compression cycle duration, and the increase is most significant in the first month. Compression set decreases, however, with rebound period and can drop to as much as ½ of that reported by manufacturers for very long rebound durations.
- For specimens held at elevated temperature, compression set is higher than the ambient temperature counterpart and increases slightly with compression cycle duration. Compression set decreases with rebound period, however only slightly. The "permanent" compression set in these specimens can be several times greater than that reported by manufacturers when determined in accordance with ASTM D3575.
- All specimens produced maximum elongations in tension in the 70-100% range, far surpassing 20-30% reported by manufacturers, which suggests the tensile capacity of foams that are appropriately bonded to the substrate are as-good or better than that reported by manufacturers, even in the presence of compression set of the foam.
- CCFs have three main failure modes in tension: failure of the bond, failure of the foam at the foam-bond interface (exterior grooves), and failure of the foam in its interior. The last of these failures modes can be precipitated by a failure to remove excess adhesive from the foam during installation. This stresses the importance of quality control during installation, to achieve optimal performance of the joint.

Recommendations

The findings of this task sub-investigation suggest several recommendations for those involved with the design and maintenance of CCFs as they apply to bridge joints. If it is determined that the compression set of a foam product is vital to its performance, then the values reported by the manufacturer should be utilized very cautiously. Especially in locations where temperatures are expected to reach high levels (100-110°F) for sustained periods of time, more conservative values of compression set (30-35%) should be assumed, as opposed to values reported by manufacturers (9-10%) who test in accordance with the current ASTM standard. Since compression set was not able to be confirmed as the primary cause of reported CCF failures in tension, limiting their application to bridge joints that only experience compression is still a conservative method for ensuring positive performance. However, in situations where CCFs are expected to perform in tension, a greater emphasis must be placed on proper installation. Tensile performance is completely reliant on a strong bond, which requires a strict

adherence to the prescribed installation procedures. Investing more time and effort into the installation process will have the greatest effect on ensuring the reliable performance of a CCF in tension.

ASTM D3575 is not entirely appropriate for testing CCF's for bridge joint applications. Modifications to the standard should be considered that would make the test more suitable for this application. Recommended changes would include increasing the compression cycle duration, testing at temperatures that are more appropriate for bridge joints in hotter climates, and increasing the rebound duration. All of these changes will yield results for compression set that are more reflective of the in-service conditions of bridge joints.

5. Procedures for Replacement, Repair, and Maintenance of Small Movement Bridge Joints

The primary objective of Task 4 of the project was to develop procedures for replacement, repair, and maintenance of small movement bridge expansion joints. The procedures were developed and presented in the Task 6 Interim Report. The outline for the procedures was:

1. Definitions
2. Types of Joints
3. Procedure for Evaluating Joints
4. Procedure for Calculating Joint Movement
5. Procedure for Selecting a Replacement Joint
6. Procedure for Replacement, Repair, and Maintenance of Asphalt Plug Joints
7. Procedure for Replacement, Repair, and Maintenance of Compression and Bonded Seal Joints
8. Procedure for Replacement, Repair, and Maintenance of Strip Seal/Armored Joints
9. Procedure for Replacement, Repair, and Maintenance of Pourable Joints
10. Procedure for Replacement, Repair, and Maintenance of Open/Siding Plate/Butt Joints

These procedures became the basis for the eventual proposed guidelines, which are presented as a standalone document in "Guidelines for Maintaining Small Movement Bridge Expansion Joints – Final Report (Part 2)". Some changes and modifications were made to the procedures in the process of developing the guidelines, but for the most part they are as found in the procedures, thus are not presented again here.

6. Summary and Conclusions

The objective of this project was to develop proposed guidelines for maintenance, repair, and replacement of small movement bridge expansion joints. It involved conducting a literature survey, conducting a survey of stakeholders to determine the state-of-practice, gathering information, and conducting a limited series of tests. All of this was used, in the end, to develop the proposed guidelines, which are presented in Part 2 of the final report, as a standalone document. The guidelines have been reviewed by the project panel, as well as other stakeholders in the industry – the comments and feedback from these groups have been incorporated into the final proposed guidelines, as the research team deemed appropriate.

The proposed guidelines stand as a comprehensive resource for bridge owners, engineers, maintenance and operation personnel, contractors, consultants, and suppliers to assist in evaluating the condition of joints, determine what remedial action should be taken for a damaged or deteriorated joints, how to select a replacement joint based on key performance metrics, and detailed procedures for replacement, repair, and maintenance of small movement bridge joints. It is hoped that with the adoption of these proposed guidelines, owners can begin to see longer life joints and reduced costs associated with deteriorated joints.

Time and again, throughout the conduct of this research, it was stated how critically important workmanship and training are to the long term performance of small movement joints. The quality of the installation of a joint can have a tremendous impact on how well it performs, for years to come. Quality of the install is affected by time, materials, environmental conditions, and training of the crew. Most supplies will offer to have a representative on-site during an installation, but this may not be enough. Maintenance crews and contractors need to be trained, and in some cases certified, to complete the work. Training may be provided by the manufacturer, perhaps through a certification program, or perhaps through web-based training. Training also comes with experience. Owners may also want to consider requiring warranties on their joints or pre-qualifications.

Implementation Plan

The problem statement for this project was originally developed and proposed by the Bridge Technical Working Group (BTWG) of the AASHTO Subcommittee on Maintenance. The guidelines will be turned over to the BTWG for their consideration. It is anticipated that the BTWG will review the document and if it deems it acceptable, perhaps with some revisions, will move towards publishing it as an official AASHTO report/document.

Future Work

The results of this investigation highlighted several topics for potential future work in small movement expansion bridge joints, these are outlined below.

1. A limited study was conducted to investigate compression set of closed cell foams. The study was informative and provided much needed and new information about this behavior, which has limited the use in some cases of closed cell foam seals. The industry, however, would benefit from a more broadly based test program of small movement bridge joints and joint systems. Such a program would establish a series of standard tests that all joints would be subjected to, and provide a standard for evaluating and reporting of the results. In this way, owners, consultants, and contractors would be in a better position to compare products/systems. The program should involve not only material tests, but tests of joint systems. Systems should include, for example, but not limited to: tests of bonded joints that include the seal, adhesive, and substrate; tests of complete asphalt plug joints; and tests of full header/seal joint systems. The material/system tests should expose the joints to the range of loads, movements, and environmental conditions that they are expected to perform in service.
2. Joint manufacturers today are not required to adhere to standardized testing of their products. The lists presented in Chapter 4 highlight the fact that currently manufacturers pick and choose the material tests to conduct and report for their products. Again, this makes comparing seals, header materials, and systems very difficult. Work needs to be conducted to develop the list of standard tests that products would be tested for. This could be done in independent of the test program listed in item 1 above, or in combination with that work.
3. The industry would benefit from having a standard protocol for conducting a field demonstration project of a joint system. Many states do this type of demonstration already as a way of proofing a new seal material or joint system; however, there is no standard for how the demonstration should be conducted, reported, or evaluated. While still allowing flexibility, the standard would outline how the demonstration should be conducted, what data and information should be recorded and how often, and how the performance of the joint should be documented at the end of the demonstration. Having a standard protocol that all owners could use would facilitate the sharing of results between owners, and would reduce the need for a vendor to conduct demonstrations with many different owners.
4. Finally, in the survey conducted three out of the four stakeholder groups said that life-cycle-cost of a joint would be a very effective performance metric. They all agreed, however, that collecting the data to do a LCC analysis would be difficult. Furthermore, not one owner said that they currently conduct LCC's for joints. Work needs to be conducted to determine exactly what data needs to be collected, how often it needs to be collected, how it is recorded and stored, so that LCC analyses can be conducted. The work should include a demonstration of LCC analysis of joints using actual data from at least two owners. The case study should also demonstrate how the data can and was used in the decision making process for how to maintain, repair, or replace joints for sample projects.

7. References

AASHTO M 297-10 (2015) "Standard Specification for Preformed Polychloroprene Elastomeric Joint Seals for Bridges," American Association of State Highway and Transportation Officials. Washington, D.C.

ASTM Standard D3575-08, (2016), "Standard Specification for Preformed Polychloroprene Elastomeric Joint Seals for Bridges," ASTM International, West Conshohocken, PA.

ASTM Standard D3575-14, "Standard Test Methods for Flexible Cellular Materials Made From Olefin Polymers," ASTM International, West Conshohocken, PA, 2014, DOI: 10.1520/D3575, www.astm.org.

ASTM Standard C70-13, "Standard Test Method for Surface Moisture in Fine Aggregate," ASTM International, West Conshohocken, PA, 2013, DOI: 10.1520/C0070-13, www.astm.org

Barnard, C.P. and Cuninghame J.R., (1997), *Improving the Performance of Bridge Expansion Joints: Bridge Deck Expansion Joint Working Group Final Report*, TRL Report. Crowthorne: Transport Research Laboratory, Print. p. 92.

Burke, Martin P. (1989) *NCHRP Synthesis of Highway Practice 141: Bridge Deck Joints*. September, 1989. Transportation Research Board, National Research Council. Washington, D.C.

Caicedo, J. M., Rizos, D., Wieger, G., Ziehl, P. (2011) Simplifying Bridge Expansion Joint Design and Maintenance. October 19, 2011. Department of Civil and Environmental Engineering, University of South Carolina. Columbia, SC. (Report No. FHWA-SC-11-03)

Chang, L. M., and Y. Lee. (2001) Evaluation and Policy for Bridge Deck Expansion Joints. Publication FHWA/IN/JTRP-2000/01. Joint Transportation Research Program, Indiana Department of Transportation and Purdue University, West Lafayette, Indiana, 2001. doi: 10.5703/1288284313206.

Dahir, Sabir H. and Mellott, D.B. (1987), "Bridge Deck Expansion Joints" Transportation research record 1987: 16-24. Transportation Research Board, Washington, DC

Johnson I.D. and Mcandrew S.P., (1993) *Research in the Condition and Performance of Bridge Deck Expansion Joints*, TRL Report. Crowthorne: Transport Research Laboratory

LRFD Bridge Design Specification (2015), American Association of State Highway and Transportation Officials, Washington, D.C.

Manual for Bridge Element Inspection (2013), American Association of State Highway and Transportation Officials. Washington, D.C.

Maintenance Manual for Roadways and Bridges (2007), American Association of State Highway and Transportation Officials. Washington, D.C. (Section 3.1.3.13)

Marques Lima, A.J. and Brito, J. (2006), "Road bridge expansion joints: Existing systems and most common defects." Proceedings of the 3rd International Conference on Bridge Maintenance, Safety and Management - Bridge Maintenance, Safety, Management, Life-Cycle Performance and Cost. Taylor & Francis Group, London UK, pp 233-234.

Marques Lima, A.J. and Brito, J. (2010), "Management System for Expansion Joints of Road Bridges," Structure and Infrastructure Engineering: Maintenance, Management, Life-Cycle Design and Performance, 6 Vol., No. 6 Taylor & Francis, London, UK., pp. 703-714

Malla, R. B., Shaw, M. T., Shrestha, M.R., Boob, S. (2006) Sealing of Small Movement Bridge Expansion Joints. University of Connecticut Department of Civil and Environmental Engineering and The New England Transportation Consortium. (Project No. 02-6)

Malla, R. B., Shaw, M. T., Shrestha, M.R., Boob, S. (2011a) Sealing of Small Movement Bridge Expansion Joints – Phase 2: Field Demonstration and Monitoring. University of Connecticut Department of Civil and Environmental Engineering and The New England Transportation Consortium. (Project No. 02-6 Phase 2)

Malla, R. B., Shrestha, M.R., Shaw, M.T., Brijmohan, S.B., (2011b), “Temperature Aging, Compression Recovery, Creep, and Weathering of a Foam Silicone Sealant for Bridge Expansion Joints,” Journal of Materials in Civil Engineering. 23 Vol. American Society of Civil Engineers.

Milner, M.H. and Shenton III, H.W. (2014), “Survey of Past Experience and State-of-the-Practice in the Design and Maintenance of Small Movement Expansion Joints in the Northeast,” AASHTO Transportation System Preservation Technical Services Program (TSP2); http://sites.udel.edu/dct/research/publications/soils-structures-and-bridges/

Mogawer, W. S., Austerman, A.J. (2004) Evaluation of Asphaltic Expansion Joints. University of Massachusetts Dartmouth Department of Civil and Environmental Engineering and The New England Transportation Consortium. (NETC 99-2)

Price, A.R. (1984), *The Performance in Service of Bridge Deck Expansion Joints*, TRRL Laboratory Report (Transport and Road Research Laboratory, Great Britain) 1984.

Purvis, Ron. (2003) *NCHRP Synthesis of Highway Practice 319: Bridge Deck Joint Performance*. Transportation Research Board, National Research Council. Washington, D.C.

Purvis, R.L. and Berger, R.H., (1983), “Bridge Joint Maintenance,” Public works 114.1 1983: 30-32. [Municipal Journal & Engineer.

Wolde-Tinsae, A.M., Klinger, J.E., and Mullangi, R. (1988), *Bridge Deck Joint Rehabilitation or Retrofitting*, Maryland State highway Administration, Baltimore, MD.

Wong, C.K. (2006), "An overview of the performance assessment method for bridge expansion joints." Proceedings of the 11th International Conference of Hong Kong Society for Transportation Studies: Sustainable Transportation. Hong Kong Society for Transportation Studies Limited pp. 541-548.

Yu, T., Li, C., and Wu, S. (2009), “Performance of Polymer Modified Asphalt Bridge Expansion Joints in Low-Temperature Regions”, Journal of Performance of Constructed Facilities. Vol. 23, Vol. American Society of Civil Engineers.

Appendix A – Stakeholder Survey