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Title: Testing of long-term performance of bridge expansion joints – a critical factor in minimizing life-cycle costs

Abstract: Modern bridge structures must be constructed to withstand higher demands than ever before, as a result of greater slenderness and increased traffic loading. Bridge expansion joints are particularly sensitive to such demands as they have to accommodate increased movements and withstand the impacts from greater traffic volumes. The long-term performance of these critical bridge components, and their fatigue performance in particular, should thus be a key factor in their selection and design. Fatigue testing of bridge expansion joints to verify long-term performance, in accordance with AASHTO LRFD Bridge Construction Specification requirements, is discussed, with particular reference to the most versatile type of expansion joint available: the modular joint. By ensuring that a particular type of modular expansion joint has successfully completed such testing in advance of use in a particular structure, the responsible engineers can minimize the amount of maintenance and replacement effort required by the bridge's expansion joints throughout its service life.

Keywords: modular joint, test, fatigue, AASHTO, Angus L. Macdonald

Introduction:

Laboratory testing of bridge components has an important role to play in verifying their long-term performance and thus minimizing their life-cycle costs. As noted by Spuler et al (2012), the life-cycle costs of a bridge’s expansion joints are likely to be many times higher than the initial supply and installation costs. An expansion joint that offers better durability will, of course, need to be replaced fewer times during the bridge’s life of 100 years or more, and it is during replacement works that the most significant costs of an expansion joint, to the bridge’s owner and its users, arise.

The long-term performance of these critical bridge components, and their fatigue performance in particular, should thus be a key factor in their selection and design. While the long-term performance of a particular type of expansion joint, as manufactured by a particular supplier, can in many cases be evaluated on the basis of the performance to date of expansion joints that have been in service for many years, it is often desirable to require evidence in the form of standardized laboratory testing, as discussed below.

1 THE TENSA-MODULAR EXPANSION JOINT

Modular expansion joints (Figure 1) have a great deal to offer the designers and constructors of bridges everywhere, thanks to their ability to facilitate very large longitudinal movements and their great flexibility - no other type of joint can accommodate longitudinal movements of two meters or more while, where so designed, also facilitating movements in all directions and rotations about all axes. This has led to modular expansion joints being the preferred solution for many of the world’s largest bridges in recent years, and to an increasing focus on performance standards and testing requirements for such joints by owners and engineers.

Figure 1. A modular expansion joint, viewed from above, showing the centerbeams and edgebeams that form its driving surface.

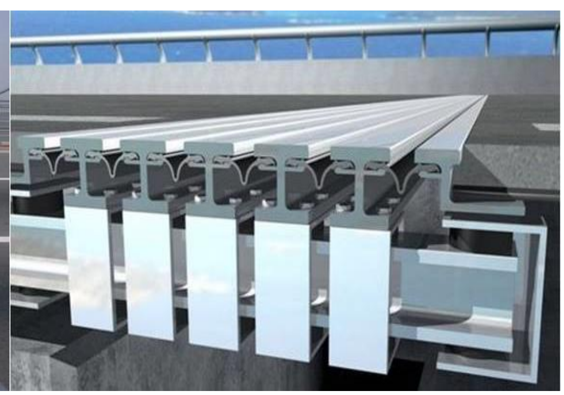

Figure 2. Representation of an installed Tensa-Modular expansion joint (cross section at a support bar), showing stirrup connections to

Figure 3. Installation of a Tensa-Modular expansion joint on a bridge with a concrete deck.

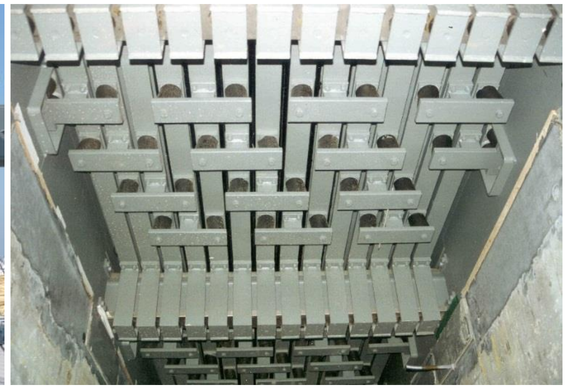

Figure 4. An installed Tensa-Modular expansion joint, viewed from below.

Modular expansion joints divide the total longitudinal movement requirement of the superstructure among individual, smaller gaps. The gaps are separated by centerbeams, which create the driving surface and which are supported at regular intervals by support bars underneath. The gaps are made watertight by means of rubber sealing profiles. Tensa-Modular is a modular expansion joint of the single support bar type (with every support bar supporting all centerbeams), with pre-stressed, free-sliding, bolted stirrup connections between centerbeams and support bars (see Figures 2 to 4). The support bars themselves are supported by a similar system in the joist boxes at each end. Rubber control springs, positioned in sets below the centerbeams, coordinate the movements of the centerbeams. This elastic system avoids constraint forces and reduces the effects of loading on the joint and on the main structure, extending the life of the entire system.

2 FATIGUE TESTING OF MODULAR JOINTS – THE AMERICAN CONTEXT

In the American context, fatigue testing of modular expansion joints is specified, among many other aspects of bridge construction, by the American Association of State Highway and Transportation Officials (AASHTO) in its LRFD Bridge Construction Specifications (AASHTO, 2004). The section of these specifications that deals with testing of modular expansion joints, Appendix A19, was based on a detailed 1997 report by the Transportation Research Board of the National Research Council. This report, entitled “Fatigue Design of Modular Bridge Expansion Joints” (Dexter et al, 1997) was issued as Report No. 402 of the National Cooperative Highway Research Program (NCHRP), and was based on research which was sponsored by AASHTO in cooperation with the Federal Highway Administration, United States Department of Transportation. A subsequent report on modular expansion joints by the NCHRP, Report 467 from 2002 (Dexter et al, 2002), noted: “When the root cause of an overall failure is a failure of the structural supports (i.e., the centerbeams and the support bars), it is usually the result of fatigue cracking. Research was previously conducted on this problem, and fatigue design and testing specifications were proposed in NCHRP Report 402. It is believed that implementing the design and testing specifications proposed in NCHRP Report 402 can substantially reduce the occurrence of fatigue cracking”. NCHRP Report 402 can thus be recognized as having a great deal of legitimacy, and the testing it defines is the most comprehensive fatigue testing currently specified by any major authority with responsibility for bridge expansion joints.

NCHRP Report 402 presents a practical test procedure for the determination of the fatigue resistance of critical details in the joint's construction. The onerous testing required by this report, and consequently by AASHTO's LRFD Bridge Construction Specifications, simulates the fatigue-inducing movements and stresses of a service life on a full-scale section of a joint which contains all critical members and connections. It involves the subjecting of expansion joint specimens to an enormous number of load cycles, and its complexity increases with the complexity of the expansion joint itself. For a highly developed and particularly flexible type of modular joint such as Tensa-Modular, fatigue testing can be especially demanding.

Although fatigue testing is specified in great detail by NCHRP Report 402, one critical aspect is not clearly defined: the number of cycles to which each test specimen must be subjected. Although a lower bound of 200,000 cycles is indicated, this is far too low to be of any practical use today. In the past, a figure of two million load cycles was commonly applied in fatigue testing of expansion joint types and components. Although this figure appears to be very high, it can quickly appear entirely inadequate when the number of axle loads to which an expansion joint is subjected during a typical service life is considered. Supposing a bridge is crossed by 30,000 vehicles per day in each direction, this would result in approximately one billion axle loads during a service life of 40 years. But testing with just a few million cycles is indeed adequate, as explained below.

3 FATIGUE PERFORMANCE AND TESTING – AN INTRODUCTION

To understand fatigue performance of a device, such as an expansion joint, which is primarily made of steel, it is helpful to consider first the fatigue performance of steel in its simplest form - as a pure material. Fatigue performance is commonly represented by an S-N curve - a graph of the magnitude of a cyclic stress (S) against the number of cycles to failure (N), with N being on a logarithmic scale (see Figure 5). Typically, as might be expected, the higher the stress, the lower the number of cycles that will cause failure. As a consequence, the parameters (S and N) for testing fatigue performance can be selected anywhere along the S-N curve, in the knowledge that satisfying the requirements (i.e. achieving results above the curve on the graph) at any point on the curve is equivalent to satisfying requirements at any other point. Of course, for practical reasons, it is preferable to minimise the number of cycles required in testing by selecting a point as close to the left end of the curve as possible (avoiding the need for hundreds of millions of cycles if a point further to the right is chosen).

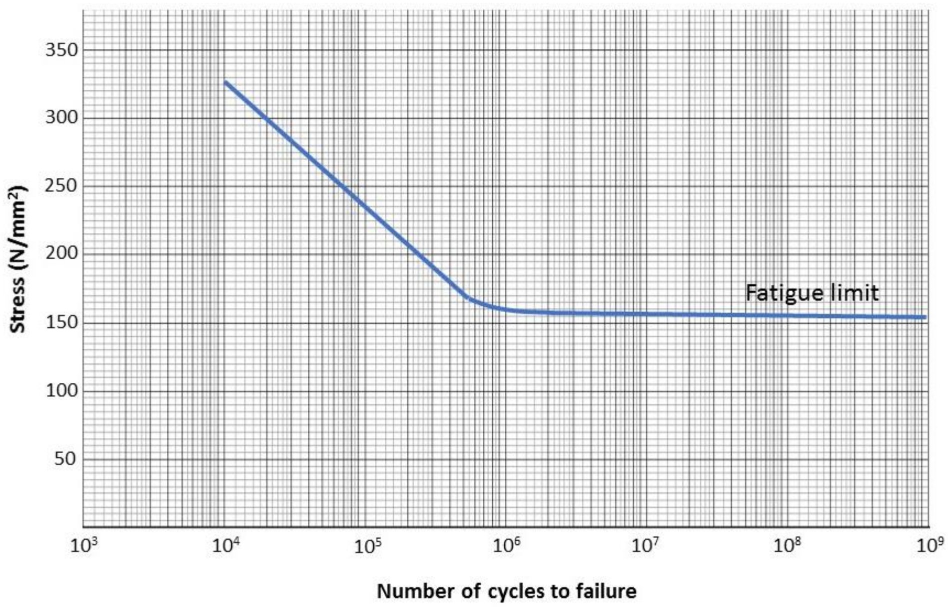

Figure 5. S-N curve for a typical steel.

A peculiarity of the fatigue performance of steel provides further insight into why testing with “just” a few million cycles can provide great confidence in real-life performance with a billion load cycles or more. For ferrous alloys such as steel, as the applied cyclic stress on an S-N curve reduces from a high level, the number of cycles to failure increases – but when the applied stress reaches a certain limiting value, the number of cycles to failure suddenly appears to approach infinity. This value is known as the material’s fatigue limit. In other words, at stresses below the fatigue limit, fatigue failure will never occur – and the S-N curve becomes horizontal at the fatigue limit, as can be seen in Figure 5. Therefore, it makes sense to conduct testing, where possible, with parameters that are taken from the flat part of the S-N curve. Such testing, in the so-called “infinite life regime”, indicates that an infinite number of load cycles could be applied without failure as long as loading levels do not exceed the corresponding value that has been applied in testing.

This understanding of fatigue performance and testing of materials is of great use when applied to structures or devices such as expansion joints. Modular expansion joints, for example, are generally manufactured predominantly from steel, with welded or bolted details such as the centerbeam to support bar bolted stirrup connection of the Tensa-Modular joint. The fatigue performance of the material is adequately covered by standard material and welding specifications, so the joint-specific assessment of fatigue performance focuses on the welded and bolted details. In most fatigue design specifications for structures, the fatigue resistance of details is reflected in so-called detail categories, which can be thought of as a ranking of the severity of the stress concentration associated with the detail geometry, with each detail category being a grouping of components and details having essentially the same fatigue resistance. AASHTO bridge design specifications define Categories A to E’, Category A being the best, and represents the fatigue performance of each by means of an S-N curve (see Figure 6). As can be seen from the curves, the number of cycles (N) that can be withstood by a detail at any particular stress range increases rapidly as the detail category improves. The dashed lines on the graph indicate a limiting value of stress range, known as the Constant Amplitude Fatigue Threshold (CAFT), at which the number of cycles to failure suddenly approaches infinity – much like a material's fatigue limit as described above. The S-N curves of steel and of details manufactured from the steel are thus analogous in this respect.

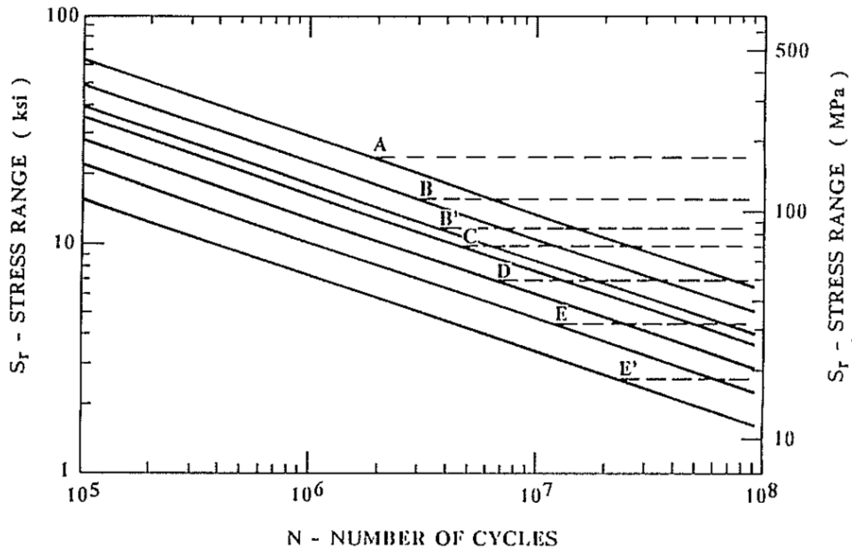

Figure 6. AASHTO S-N curves for all detail categories (Figure 2.5 of NCHRP Report 402).

The S-N curves for detail categories provide an insight into why the figure of two million load cycles has often been applied in the past in laboratory fatigue testing. As for testing of materials, it is sensible to select the parameters for testing from the point on the appropriate S-N curve where the curve becomes flat (horizontal), to minimize the number of cycles while benefitting from the infinite life regime aspect. For relatively uncomplicated expansion joint types, such as cantilever finger joints, Category A can be considered to apply, so the number of cycles, N, has often been set at two million (with the corresponding CAFT of approximately 165 MPa).

4 APPLICATION OF AASHTO FATIGUE TESTING REQUIREMENTS TO THE TENSA-MODULAR JOINT

It is desirable for an expansion joint's details to be recognised as belonging of a high category, as it provides confidence in the long-term performance of the joint and enables fatigue design requirements to be satisfied by less cumbersome, more easily installed and maintained expansion joints. Category A is typically only applicable for very simple details such as base metal with no welds or structural connections, so Category B is the best that can be realistically hoped for in relation to connections of any sort. In fact, the NCHRP Report 402 specifies that a centerbeam to support bar connection with a stirrup should be classified as Category D (unless a higher category is proven by testing).

The manufacturer of the Tensa-Modular joint, having committed to carrying out fatigue testing in accordance with AASHTO requirements, made arrangements to do so at America's leading institute in this field, the ATLSS Engineering Research Center of Lehigh University, Pennsylvania, USA. Testing of an entire expansion joint is not required, but of full-size parts which contain all relevant fatigue-sensitive details and elements. In the case of the Tensa-Modular joint, the requirements could be fulfilled by testing specimens consisting of just the critical stirrup connection between a section of centerbeam and a section of support bar beneath. Being convinced that Category B was achievable and appropriate for this connection, the company decided to conduct the testing with the objective of proving this. After extensive discussions with ATLSS, involving complex technical considerations such as real-life deviations from the idealised S-N curves mentioned above and considering the specifications of various American states, it was concluded that testing should consist of 6 million load cycles for each specimen. Although the S-N curve for Category B indicates a figure of three million at the point where the curve becomes horizontal, a factor of two is applied to this to reflect the effect of a statistical bell-curve distribution. In order for just 5% of the results represented by a normal distribution to fall below the figure of three million indicated by the S-N curve, that figure is increased by a factor of two times the standard deviation, which is evaluated by a factor of two. In effect, this introduces a much higher degree of statistical certainty to the testing; a bell-curve centred on the target value of three million load cycles (as it would be if that was the number of cycles chosen for testing) would allow 50% of the values to fall below the target figure, and thus to fall within the "finite life regime", but a bell-curve centred on a target value of six million cycles evaluates just 5% to fall below the target figure, with 95% falling within the "infinite life regime". In statistics, and thus statistics-based testing, an allowance for 5% (1 in 20) of values to fall outside proposed limits without compelling the statistician to consider these values particularly significant has been a key aspect of probability theory since Sir Ronald Fisher, the father of modern statistics, first championed the standard in 1925. In relation to the fatigue testing of modular expansion joints, the factor of two is specified, for example, by Washington State Department of Transportation, one of America's leading authorities in this field.

In accordance with AASHTO requirements, at least ten S-N data points are required to confirm that values consistently fall above the appropriate curve on the S-N graph. Four expansion joint specimens were tested, two at a time, each with three centerbeams, allowing for twelve data points in total. Testing was carried out between June 2012 and September 2013 (Figures 7 and 8), with almost continuous use of one of the industry's most elaborate testing facilities – facilities which were, in fact, used to conduct the original research relating to the development of NCHRP Report 402. The ATLSS laboratory is one of the largest of its kind in North America, with a 100 foot (30.5 m) by 40 foot (12.2 m) strong test floor, bordered on two adjacent sides by a monolithic rigid reaction wall that is up to 50 foot (15.2 m) high. The laboratory is equipped to generate multi-directional (multi-axis) static and time-varying loads, with hydraulic power systems that operate at up to 3,500 psi (24.1 MPa). These systems serves numerous, computer-driven servo-controlled hydraulic actuators simultaneously and independently using a system of six 40 gpm (150 liters/min) independent hydraulic service manifolds.

The specimens, featuring noise-reducing surface plates ("sinus plates"), were tested under constant amplitude fatigue loading, with 70% of the total load range applied downward and 30% applied upward, acting at the center of each centerbeam span. The centerbeam to support bar bolted stirrup connection was tested for a nominal stress range of 16 ksi (110 MPa), corresponding to the CAFT for AASHTO

Category B. The testing was completed successfully, with the fatigue resistance of all details being verified by testing of ten specimens as specified, each subjected to 6 x 10^6 load cycles without any fatigue cracking (run out, i.e. no failure). Special aspects such as field splicing are subject to ongoing examination.

Figure 7. Fatigue testing of Tensa-Modular joint – testing rig at ATLSS / Lehigh University.

Figure 8. Fatigue testing of Tensa-Modular joint – one specimen.

5 REFERENCE PROJECT – ANGUS L. MACDONALD BRIDGE, HALIFAX

The Angus L. Macdonald and A. Murray MacKay bridges are critically important structures for the city of Halifax, capital of the Canadian province of Nova Scotia. They were opened to traffic in 1955 and 1970 respectively, and several decades later, it was determined that both structures were in need of significant reconstruction / maintenance work in order to meet the demands of modern traffic for decades to come. The Angus L. Macdonald Bridge, in fact, is receiving an entire new deck, and computer modelling of the deck, verified by measured data, is playing a key role in the design process. The A. Murray MacKay Bridge, on the other hand, is retaining its existing deck, but is being subjected to significant renovation work.

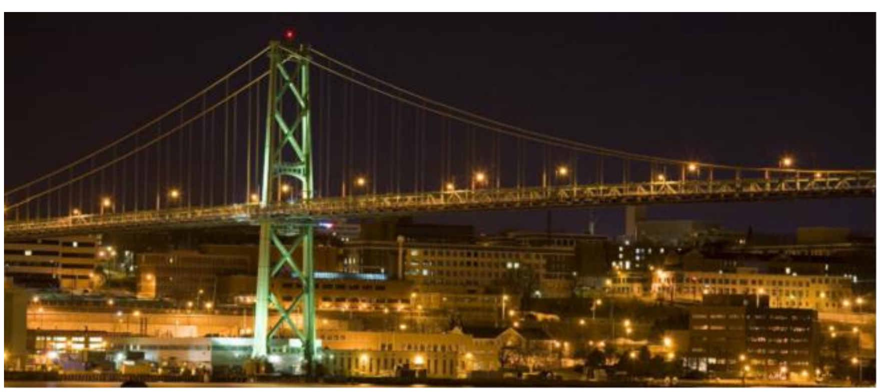

Figure 9. The Angus L. Macdonald Bridge, Halifax.

Early in the project, it was determined that a fully automated Robo-Control structural health monitoring (SHM) system should be used to measure and record the movements and rotations of the bridge decks.

The installed system has provided the data needed by the computer modelling of the new deck of one bridge, and assisted in the planning of remedial works of the existing deck of the other, enabling the bridge's engineers to optimize their designs and minimize the life-cycle costs of the bridges.

In 2014, it was decided to install new modular expansion joints with up to seven gaps each at four axes of the Angus L. Macdonald Bridge, replacing the existing joints. These joints were to be designed for steel connection, and feature noise-reducing surfacing. In order to ensure that the bridge's new expansion joints would provide good long-term performance, and require minimal maintenance and replacement effort, the structure's owner decided to specify that the expansion joints' supplier must first demonstrate successful completion of testing in accordance with AASHTO LRFD Bridge Construction Specifications – including "infinite life regime" fatigue testing as described above with six million load cycles per specimen. The Tensa-Modular expansion joint, having successfully completed this fatigue testing and also the specified *Opening Movement and Vibration* (OMV) and *Seal Push-Out* (SPO) tests, was selected for use. These joints are to be installed in 2017, commencing what can confidently be expected to be a long, unproblematic service life.

Conclusion:

Expansion joints are arguably the parts of a bridge upon which the highest demands are placed, being relatively light compared to the rest of the structure, yet highly stressed and subject to intense fatigue loading. This is especially true of the most advanced modular joints, due to their exceptional flexibility and complex movement capabilities. The described fatigue testing of such a modular joint in accordance with AASHTO specifications – the most demanding by any major authority worldwide – demonstrated adequate fatigue performance, in the "infinite life regime", at a level of testing which is unprecedented in the industry for any type of expansion joint. It thus set a new benchmark for what can be, and arguably should be, expected by bridge owners in terms of independent verification that the modular expansion joints to be used on their structures will provide good long-term performance.

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