Fatigue testing of modular expansion joints in the infinite life regime according to AASHTO specifications

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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 expansion joint, testing, fatigue, AASHTO.

1 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.

2 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.

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 and 3). 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.

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

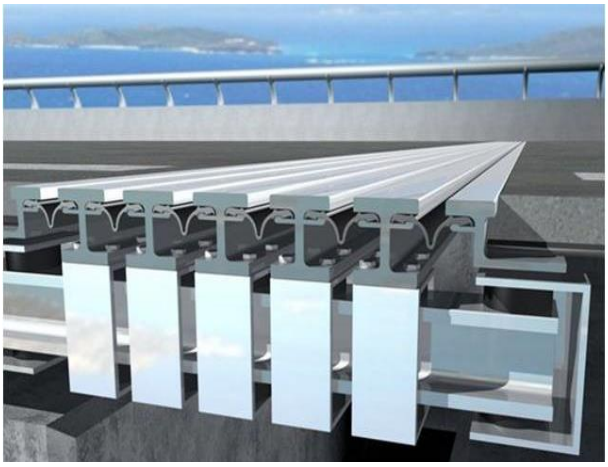

Figure 2. Representation of a modular joint of the type in question showing cross section at a support bar and stirrup connections to centerbeams

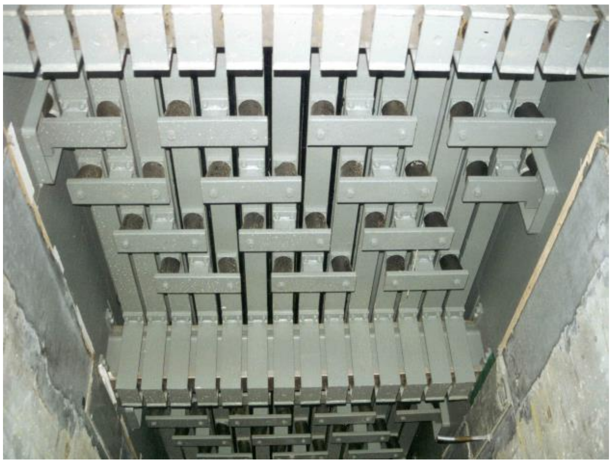

Figure 3. An installed modular expansion joint of this type, viewed from below

3 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. 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 – but also very satisfying, since the high quality and durability that result from this joint’s detailed design and manufacturing processes, its highly defined bolted connections and other factors enable it to perform excellently in testing.

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.

4 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 4). 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).

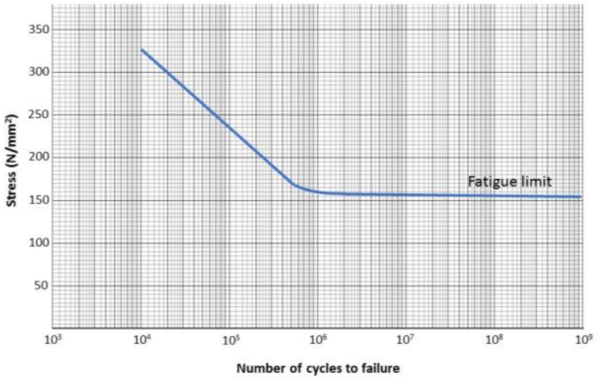

Figure 4. S-N curve for a typical steel

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 4. 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 joint type in question. 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 5). 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.

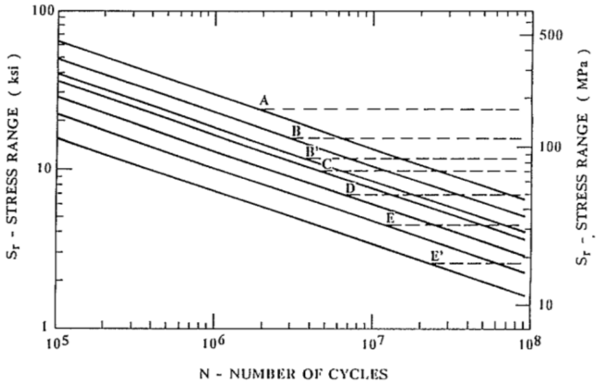

Figure 5. AASHTO S-N curves for all detail categories (Figure 2.5 of NCHRP Report 402)

5 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 no higher than Category D (unless a higher category is proven by testing). It should be noted, however, that this stipulation was based on fatigue testing of a low-quality expansion joint of a specific manufacturer many years ago, and is not realistic for a modern, high-quality modular joint.

The manufacturer of the modular joint in question, 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 modular joint type in question, the requirements could be fulfilled by testing the critical stirrup connection between a section of centerbeam and a section of support bar beneath, and adding sinus plates as appropriate. 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 – and to conduct the testing in the infinite life regime, which had never been done before for expansion joints, even though it is a clear recommendation in NCHRP Report 402. 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" (see Figure 9). 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. Fourteen specimens were tested, during three phases of the test campaign. Each specimen consisted of three centerbeams supported by three support bars, with each specimen providing a single data point (from the central centerbeam). Testing was carried out between June 2012 and September 2013 (Figures 6 to 9), 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.

The fact that the tested specimens included noise-reducing surfacing, or sinus plates, is particularly noteworthy, as such surfacing had never been subjected to fatigue testing in accordance with these standards. Although sinus plates had already been used on many modular expansion joints around the world, and some in North America such as the Port Mann Bridge in Vancouver, the successful completion of the testing quickly enabled the responsible engineers on the SR520 West bridge construction project in Washington State to specify the use of sinus plates on the large modular joints installed in the bridge – the first application of this aspect of the fatigue testing.

Figure 6. Fatigue testing of the specific type and design of modular joint – testing rig at ATLSS / Lehigh University

Figure 7. Fatigue testing of the specific joint type – one specimen

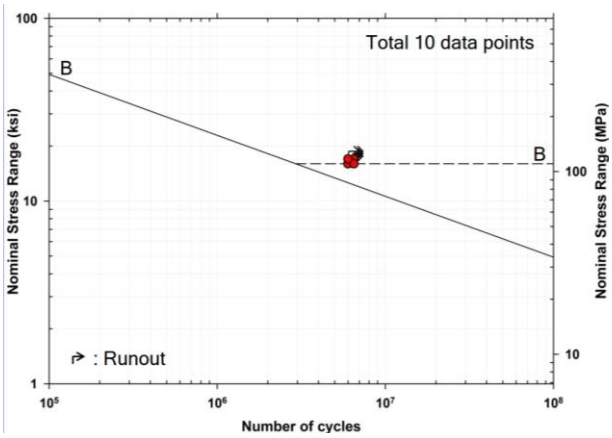

Figure 8. Results from the fatigue testing of the joint, showing a cluster of "run-out" (i.e. no failure) values at six million load cycles

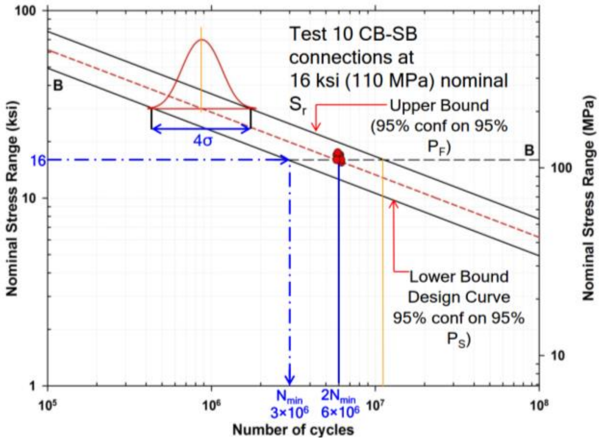

Figure 9. Illustration of the impact of – and reason for – increasing the number of load cycles from 3 million to 6 million (at the appropriate nominal stress range of 16 ksi), which reduces the probability of values falling below the new lower bound of 3 million cycles from 50% to just 5%

6 The wider impact of the conducted testing – Revisions to the AASHTO standard

In 2016, following completion of the aforementioned testing, the relevant AASHTO standard was revised in a number of ways – thanks in part to the knowledge and experience gained during this testing. The standard, and the NCHRP report (No. 402) on which the fatigue testing was based, were in some ways incomplete in their definition of how testing in the infinite regime should be carried out. The development of the necessary detailed proposals for the conducting of the fatigue testing required significant work, including consideration of the specifications of Washington State Department of Transport, one of the country's leading authorities in this field, which resulted, in particular, in the conclusion that six million load cycles should ideally be applied to prove Category B.

The revisions to Appendix A19 include, for example, a focus on all connection details (rather than just CB/SB and field weld connections, as previously). A higher minimum number of cycles is also specified, for finite and infinite life regimes.

A number of other significant revisions are described below – several of which have the purpose of ensuring that real system behavior is reproduced in the fatigue test.

1) Specific information for infinite regime testing is provided for the first time

The standard now states: "If testing is conducted in the infinite life regime of the S-N curve of a postulated detail category, the first load range shall be chosen so that the applied stress range is just above the constant amplitude fatigue threshold (CAFT) of the detail. The applicable CAFT shall be selected from those CAFT values corresponding to the AASHTO fatigue categories. The test may be considered as run-out if no fatigue crack develops after twice the number of cycles N_{min} as designated in Table 1". This corresponds directly to the factor of two that was applied to the number of load cycles used in the completed fatigue testing described in the previous section.

2) Beam support/restraint conditions must correspond to those actually arising in service.

In the past, Appendix A19 allowed shims to be placed between centerbeams at support bar locations "to prevent rotation of the centerbeams under load" (i.e. at both top and bottom flanges). However, it has been observed in field testing that the top flanges of centerbeams rotate under vehicular load, so it is now specified that shims should only restrain bottom flanges. See Figure 10.

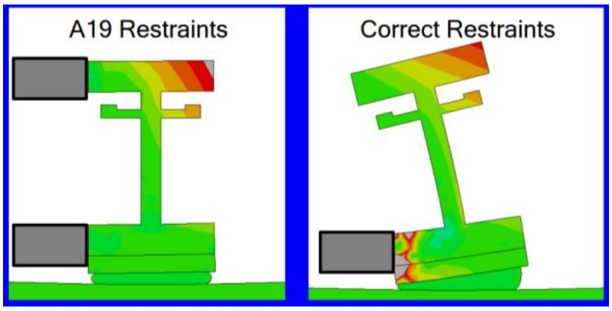

Figure 10. Centerbeam lateral restraint conditions allowed by Appendix A19 – In the past (left), and following revision (right)

3) Components should not be replaced for testing by elements that significantly change behavior

NCHRP Report 402 states that elastomeric components, including the sliding spring beneath the support bar in a stirrup connection to a centerbeam, as shown in Figure 11) "may be replaced in the fatigue test specimen with steel discs or rectangular blocks of the same dimensions". However, this has been shown to substantially change the behavior of the connection, with high prying forces acting on the bolts as the centerbeam rotates while the stirrup remains stationary (see Figure 12); with proper, high-quality elastomeric components, no bolt failure occurred with six million load cycles, whereas, with steel discs used as an alternative, bolt fractures occurred already after about 40,000 cycles.

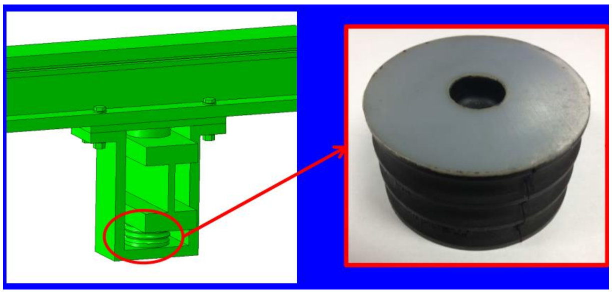

Figure 11. Illustration of a bolted stirrup connection between a centerbeam and a support bar, showing the elastomeric sliding spring beneath the support bar

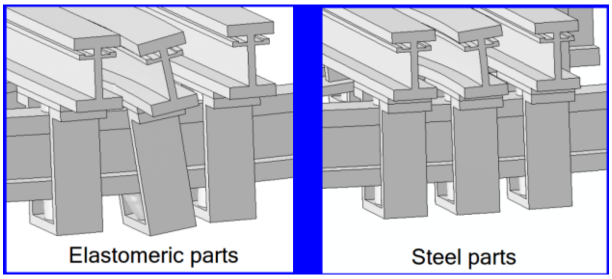

Figure 12. Illustration of the difference in behavior caused by the replacement of elastomeric sliding springs with steel discs

4) Fatigue stresses shall be based on measurements rather than on calculations

Experience has shown that the applied load for testing should be verified by strain measurements because calculations might not be able to properly represent the complex system. Strain measurements must be made in the vicinity of all fatigue tested details for use in reporting nominal stress ranges. These locations shall be sufficiently far from the target details so that they are not influenced by local effects (i.e., away from weld toes or boltholes). These measurements are to be used for estimating stress ranges at the target details, as defined in the standard.

5) Changed default/maximum permitted categories for centerbeam to support bar connections

The "default categories" for centerbeam to support bar (CB/SB) connections, previously contained in Table 2 of Appendix A19, have now been removed (Table 2 has been deleted). The default categories were to be applied in design unless a higher category was proven for the specific modular joint type and design by the (very extensive) fatigue testing. These had been determined, in NCHRP Report 402, on the basis of testing of a modular joint type of very low quality – certainly by today's standards. But thanks to the evidence provided by the completed testing, the default category (Category D) for bolted CB/SB connections, which is unrealistically low for high-quality, properly designed and detailed joints, and other default categories contained in Table 2, no longer apply to designs according to Appendix A19. Instead of defining categories in particular for centerbeam to support bar connections, Appendix A19 refers now to Article 6.6.1.2.3 of AASHTO LRFD Bridge Design Specifications. This way, fatigue design becomes much more consistent and applicable categories have a much more solid basis than if verified by finite life regime testing, with clearer definition of cases being provable by infinite life regime testing.

7 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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