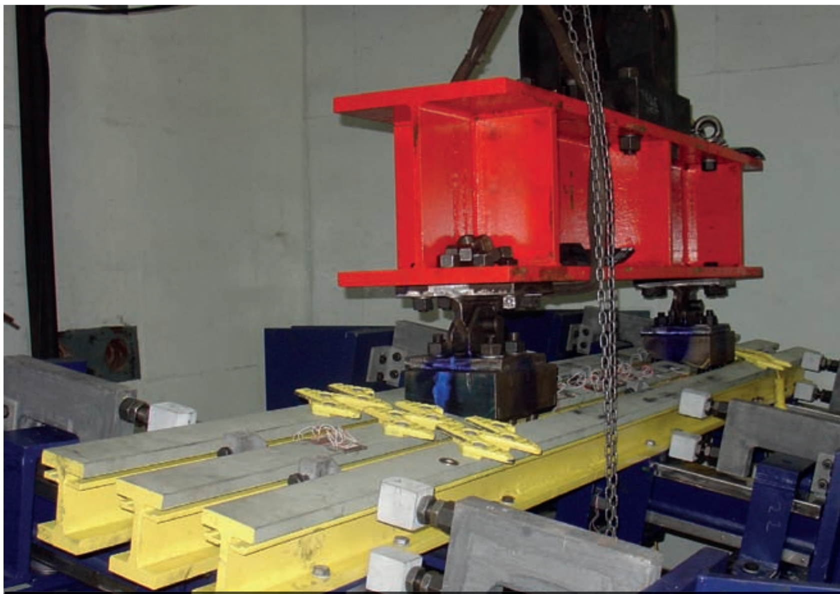
FIGHTING FATIGUE

Fatigue testing for complex joints can be particularly demanding



An extensive programme of fatigue testing was carried out at Lehigh University

Ensuring the longevity of expansion joints is key to minimising bridge life-cycle costs. **Gianni Moor**, **Simon Hoffmann** and **Colm O'Suilleabhain** report on a testing programme designed with this in mind

Laboratory testing of bridge components is important to verify their long-term performance and minimise life-cycle costs. This is especially true when the component is an expansion joint and the life-cycle in question is that of the bridge rather than the component. An expansion joint is typically far less robust than the main structure, and subjected to movements and impacts throughout its life, thus will generally have a service life that is just a fraction of the bridge. A 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 real costs of an expansion joint arise, both to bridge owner and users.

Approaches to testing of expansion joints vary depending on the region and applicable standard, and can consist of numerous tests of full-scale joint specimens or of individual components. In verifying the long-term performance of an expansion joint in the laboratory, fatigue testing is likely to provide more compelling evidence than any other type. Fatigue testing involves subjecting an expansion joint to an enormous number of load cycles, and its complexity increases with the complexity of the expansion joint itself.

For a complex joint such as Tensa-Modular – a particularly flexible type of modular joint that can accommodate movements in all directions and rotations about all axes – fatigue testing can be especially demanding. This is certainly true of the fatigue testing that US authority AASHTO specifies in its *LRFD Bridge Construction Specifications (Appendix A19)*, with reference to *Report 402* of the National Cooperative Highway Research Program. This is the most comprehensive fatigue testing currently specified by any major authority with responsibility for bridge expansion joints.

Modular expansion joints consist primarily of the surface beams that provide a driving surface for traffic – known as centre-beams if they are not fixed to the deck at either side – and support bars underneath, which support the centre-beams at regular intervals. Tensa-Modular is a modular expansion joint of the single support bar type, with bolted stirrup connections between centre-beams and support bars.

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 might seem 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 even so, testing with just a few million cycles is indeed adequate.

To understand fatigue performance of an expansion joint, which is primarily made of steel, it is helpful to first consider the fatigue performance of steel in its simplest form – as a pure material. Fatigue performance is commonly represented by a graph of cyclic stress against the number of cycles to failure, with the latter on a logarithmic scale. Typically the higher the stress, the lower the number of cycles that will cause failure. As a consequence, the parameters for testing fatigue performance can be selected anywhere along this curve, in the knowledge that satisfying the requirements at any point on the curve is equivalent to satisfying requirements at any other point. 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 and avoiding the need for hundreds of millions of cycles.

A peculiarity of the fatigue performance of steel provides further insight into why testing with 'just' a few million cycles can provide great confidence when real-life performance involves 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. 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 '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 very helpful 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 centre-beam 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.

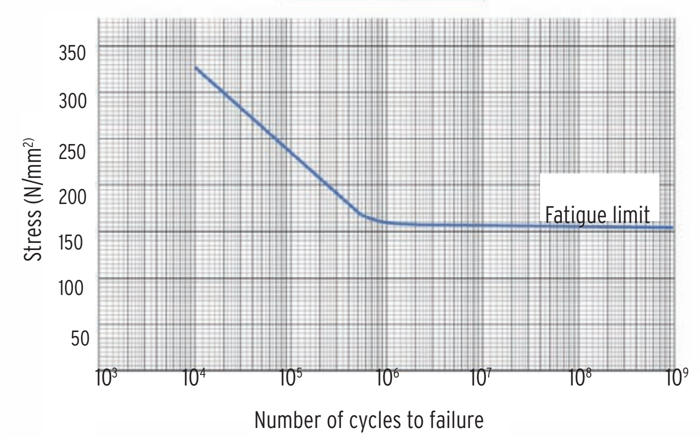
In most fatigue design specifications for structures, the fatigue resistance of details is reflected in so-called detail categories, which can be thought of as a ranking of the severity of the stress concentration associated with the detail geometry, with each detail category being a grouping of components and details having essentially the same fatigue resistance. AASHTO bridge design specifications define categories A to E, with A being the best, and represent the fatigue performance of each by means of S-N curves. The number of cycles that can be withstood by a detail at any particular stress range increases rapidly as the detail category improves. The curves have a limiting value of stress range, known as the constant amplitude fatigue threshold, at which the number of cycles to failure suddenly approaches infinity – much like a material's fatigue limit. The S-N curves of steel material and of details manufactured from the steel are thus analogous in this respect.

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 with 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, to minimise 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 has often been set at two million, with the corresponding constant amplitude fatigue threshold of approximately 165MPa.

It is desirable for an expansion joint's details to be in 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 expansion joints which can be more easily installed and maintained.

Category A is typically only applicable to very simple details such as base metal with no welds or structural connections, so 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 centre-beam/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 the ATLSS Engineering Research Center of Lehigh University in Pennsylvania, USA. Convinced that category B was achievable and appropriate for the critical stirrup connection, the company decided that the testing should be



Graph shows an S-N curve for a typical steel

conducted 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 and reviewing the specifications of various American states, it was concluded that testing should consist of six 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 equates to 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, 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 would allow just 5% to fall below the target figure, with 95% falling within the infinite life regime. This approach is specified, for example, by Washington State Department of Transportation, one of the USA'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. Testing took more than a year to complete, and involved almost continuous use of one of the industry's most elaborate testing rigs. The specimens, featuring noise-reducing surface plates, were tested under constant amplitude fatigue loading, with 70% of the total load range applied downwards and 30% applied upwards, acting at the centre of each centre-beam span.

The centre-beam to support bar bolted stirrup connection was tested for a nominal stress range of 110MPa, corresponding to the constant amplitude fatigue threshold for AASHTO category B. The testing was completed successfully, with the fatigue resistance of all details being verified by testing of ten specimens, each subjected to six million load cycles without any fatigue cracking failures. Special aspects such as field splicing are subject to ongoing examination.

The testing thus 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. This testing has 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

Gianni Moor, Simon Hoffmann and Colm O'Suilleabhain work for Mageba