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Fatigue Testing of Modular Expansion Joints for Bridges
Essais à la fatigue de joints de dilatation modulaires des ponts
Ermüdungsversuche an modularen Dehnungsfugen von Brücken

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SUMMARY
Strain-gage testing on a modular expansion joint system revealed aspects of the load distribution which are difficult to predict from analysis. The system, with a partial-penetration connection detail, was subjected to over two-million cycles of loading without cracking. Subassemblies were also tested, and it was shown that the full-penetration connection detail can be designed as a Category C (Eurocode 90) detail. The stress range used to check the fatigue strength of these details in design must be the maximum range of principal stress, considering the combined stress in the detail including torsion and biaxial bending.

RÉSUMÉ
Des essais effectués sur un système de joints modulaires, pourvus de jauges de déformation, ont révélé des aspects difficiles à mettre en relief par le calcul. Constitué par un dispositif de liaison avec pénétration partielle, le système a été soumis à plus de deux millions de cycles d'efforts alternés, sans entraîner de fissures. D'autres types de joints à assemblage partiel avec pénétration totale ont été également testés, montrant que ce type de joint peut correspondre à celui de la catégorie C (Eurocode 90). Le domaine de contraintes des essais à la fatigue doivent englober la plage maximale de la contrainte principale, en tenant compte de la superposition de la flexion biaxiale et de la torsion.

ZUSAMMENFASSUNG
Versuche mit Dehnungsaufnehmern an einem modularen Fugensystem brachte Erkenntnisse, die durch Berechnung schwer zu gewinnen sind. Das System, bestehend aus einer Verbindungsvorrichtung mit teilweiser Durchdringung, wurde mehr als zwei Millionen Lastwechseln unterworfen, ohne Risse zu verursachen. Teilkonfigurationen wurden ebenfalls getestet, und es zeigte sich, dass die Verbindungsvariante mit voller Durch-dringung als Fuge nach Kategorie C des Eurocodes 90 gestaltet werden kann. Das Spannungsregime für die Ermüdungsprüfung muss die Maximalamplitude der Hauptspannung mit Berücksichtigung der Ueberlagerung von Torsion mit Doppelbiegung in der Fuge, umfassen.

1. INTRODUCTION

Drainage and debris through open expansion joints has been a major cause of corrosion damage in bridges. Modular bridge expansion joints (MBEJ), shown schematically in Figure 1, are sealed and prevent drainage through the deck joint. The transverse beams between the seals are called centerbeams, and each centerbeam is supported on an independent series of support bars which span in the longitudinal direction between support boxes which are cast into the concrete haunches. Inside the support boxes, the support bars slide between precompressed springs and bearings. The transverse beams at the edges which are cast into the concrete haunches are called edgebeams. Since expansion joints are subject to almost exclusively live load, the fatigue limit state will typically govern the design. However, there are no fatigue design specifications for MBEJ in the USA and they are procured by a lowest-bidder process. The competitive nature of the marketplace has led to decreased margin of safety against fatigue, and premature failures have occurred in a few cases. Several different types of fatigue tests were conducted to develop design guidance.

2. TESTS ON THREE-SEAL SYSTEM

Static strain-gage testing and fatigue test were conducted on the three-seal modular expansion joint as shown in Figure 2. A three-span length of this system (including seals, springs, bearings, and support boxes) was subjected to loads applied through a truck axle with wheels and tires. The fatigue test on the three-seal system was conducted with a 186 kN axle load, which corresponds to the HS20 truck (see Article 3.7.6 of the AASHTO "Standard Specifications for Highway Bridges" [1]) with a 30 percent impact factor applied. This axle load (hereafter referred to as the design load) is more than twice as large as would normally be allowed for the tires. The joint was inclined relative to the loading axis so that the loading contained a component parallel to the plane of the joint ("horizontal" load) equal to 20 percent of the load normal to the plane of the joint ("vertical" load). The horizontal load of 20 percent of the vertical load is consistent with field measurements and the recommendations of Tschemmernegg [2] as well as a specification from the State of Washington [3].

2.1 Static Strain-Gage Tests and Comparison to Analysis

Static tests were conducted at various seal gaps. The width of the contact area of the tire against the joint (in the direction along the centerbeams) was relatively constant at 560 mm because the sidewalls of the tire are relatively rigid. The length of the contact area increased with load up to about 330 mm at the design axle load. Typically, the measured stress ranges in the system can vary about 50 percent between locations that ought to have similar results. Our experience with strain-gage testing of complex systems indicates that this much variation is expected. Bending moment diagrams in both the centerbeams and support bars were "fit" to the measured strains, which helped to reduce the apparent variation in results. The support bar reactions were computed from the bending moment diagrams. A comparison of the bending moment in the primary centerbeam (i.e. that centerbeam directly under the tire) at different gap widths shows that the load in this centerbeam is not sensitive to the gap width. This finding is reasonable because the load on the centerbeam is limited to the product of the tire air pressure and the contact area with the centerbeam. For the 38 mm gap with air in the tires, the share of the load in the primary centerbeam decreased from about 55 percent at low loads to about 40 percent at the design load. The 40 percent share is in reasonable agreement with previously published design recommendations [1,2].

A linear three-dimensional frame analysis was made of one centerbeam with the ends of the support bars pinned in both directions. This analysis is a stick model, i.e. the members all lie in the same plane and have infinitesimal thickness. Forty percent of the load was assumed to be acting on the centerbeam and the load included a 20 percent horizontal component. The three-dimensional analysis gives strong-axis bending results which are very similar to the results from a continuous beam model with rigid supports. The computed strong-axis bending is in good agreement with measurements at load levels up to 60 percent of the design load (i.e. in the range of realistic axle loads). However, at higher load levels, the rate of increase of the measured strong-axis bending moments with load decreases. Therefore, other load paths must develop as the load is increased which are not predicted by the analysis. Results for the weak-axis (horizontal) bending case show that the predicted horizontal moments in the centerbeam are about equal to 10 percent of the vertical moments. Part of the horizontal bending moments are transmitted to the support bars as the joints rotate. The ten percent ratio is generally consistent with the measurements, where the ratio varies from about 5 to about 10 percent.

The tires appeared significantly distressed at the design load and it was judged that they would probably soon fail if cycled at this load. Therefore, it was decided to perform the fatigue test with concrete in the tires. The footprint of the concrete-filled tires was formed to have a 280 mm footprint (between the AASHTO and actual measurement for the air-filled tires corresponding to the design load). For the midrange seal gap which was used in the fatigue tests (38 mm), there was reasonable agreement between the bending moments at the design load from tests with concrete-filled tires and the tests with air-filled tires.

2.2 Fatigue Test

The objective of this test was to demonstrate that the particular size modular expansion joint system that was tested could withstand more than two million cycles of the design loading. This objective differs from the typical objective of fatigue testing which is to get the number of cycles to failure to identify the appropriate S-N curve for certain details which failed. Valid tests to characterize the fatigue strength must be full-scale and, if there is biaxial loading, the proportion of the loads is important. In typical fatigue testing of components of the system, structural analysis is required to transfer the test results to the actual joint geometry. As discussed above, the static testing showed significant variation in measured strains which vary in a nonlinear manner with respect to load, and vary from the analytical results by as much as 50 percent. There are probably many different factors that cause this variation which are not considered in the analysis. The closer the configuration and design loading conditions are to the conditions in the test, the better. Therefore, due to the unreliability of stress analysis, the full-scale system proof test is advantageous because structural analysis is not required to interpret or use the results.

A partial-penetration connection detail was used for the centerbeam-to-support-bar joints in this system. The fatigue tests were conducted between 1 and 2 Hz (much slower than actual truck impact) with a very small minimum load (about 9 kN). After 2.05 million cycles were applied, the test specimen was disassembled and visually inspected for cracks. No cracks were found, indicating the test passed. A single fatigue test was also conducted on an elastomeric bearing. This test indicated that it is likely that the fatigue strength of the bearings is also sufficient to withstand more than 2 million cycles of HS20 loading with 30 percent impact.

3. SUBASSEMBLY TESTS

Fatigue tests were also conducted on three specimens, each of which consisted of three spans of a single centerbeam on four support bars as shown in Figure 3 A full-penetration welded connection detail was used in this subassembly test. The objectives of these subassembly tests were to characterize the fatigue strength of the full-penetration weld details in terms of the appropriate detail category or S-N curve. Two 280 mm long line loads centered 1830 mm apart were applied to the centerbeam to simulate axle loading. The specimens were inclined so that the load produced a horizontal component which was equal to 20 percent of the vertical component. The applied total load ranges were 390 kN, 260 kN, and 180 kN.

The centerbeam is in a state of biaxial bending. Therefore, the proper stress range for checking the centerbeam at the point of midspan maximum moment is the sum of the extreme fiber stress for vertical and horizontal bending. There is torsion in the centerbeam as well, but at this location the torsion causes only shear stresses and can therefore be ignored. The data from these base metal failures all fall above the Category A S-N curve, the equivalent of the Eurocode 160 S-N curve [4], as expected.

In the connection of the centerbeam to the support bar, the maximum stress range occurs where the applied stresses remain in compression. Cracks can form because there is generally high tensile residual stress so that the sum of residual plus applied stresses is at least partly in tension as the stress fluctuates. Figure 4 shows a typical crack which occur at the full-penetration connection detail. Note that the cracks are inclined at about 45 degrees. The cracks grow in the plane normal to the principal stress axis. It is clear that cracks are driven by a combination of the longitudinal bending stress in the centerbeam or support bar as well as the vertical stress range in the throat of the connection resulting from the reaction on the support bar and the bending stress due to the overturning moment in the centerbeam. The two components of the principal stress range are calculated and the total principal stress range may be approximated as the square root of the sum of the squares of the two components.

The S-N curve for the two types of cracks which occur at this connection is shown in Figure 5. Data from both types of cracks appear to belong to the same population. Most of the data are above the Category C (Eurocode 90) S-N curve, which is the expected fatigue strength for a full-penetration groove weld attachment. Before these cracks could grow to failure, the cracks developed in the centerbeams which prevented further loading. Therefore it is expected that the total number of cycles to failure would be above the Category C curve if the cracks had been able to continue to grow.

4. CONCLUSIONS

The system test demonstrated that this particular MBEJ, with a partial penetration connection detail, can withstand more than two-million cycles of the design loading. The subassembly testing characterized the fatigue strength of the details in terms of the appropriate detail category and design S-N curve. The stress range used to check the fatigue strength of these details in design must be the maximum range of principal stress, considering the combined stress in the detail including torsion and biaxial bending. The base metal, away from any weld, can be designed as an AASHTO Category A (Eurocode 160) detail. The full-penetration weld connecting the centerbeam to the support bar can be designed as a Category C (Eurocode 90) detail.

5. ACKNOWLEDGEMENT

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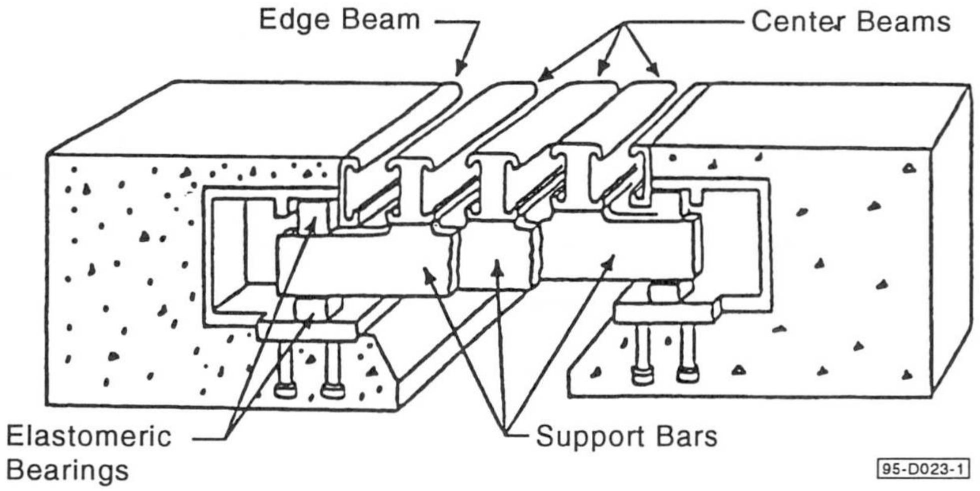

Figure 1: Schematic of modular expansion joint system

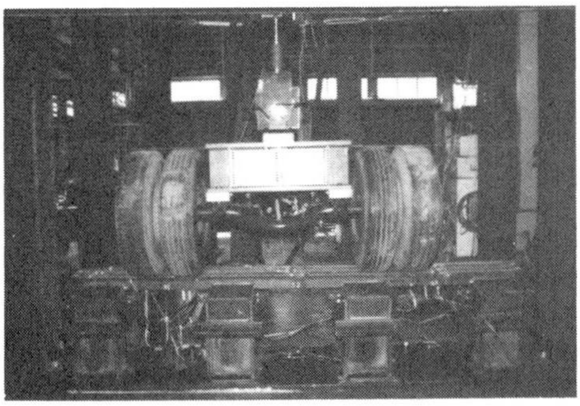

Figure 2: Full-scale system fatigue test

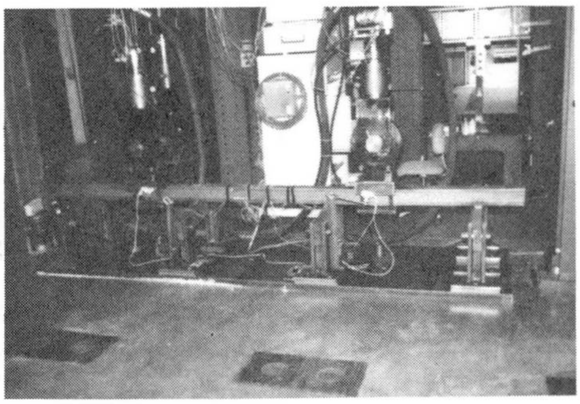

Figure 3: Single centerbeam fatigue test

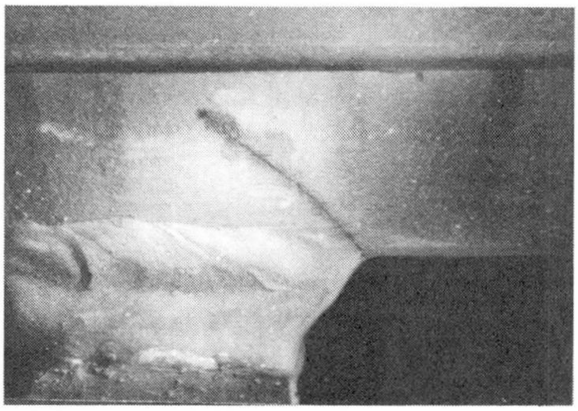

Figure 4: Typical crack in the centerbeam at the full-penetration weld connection.

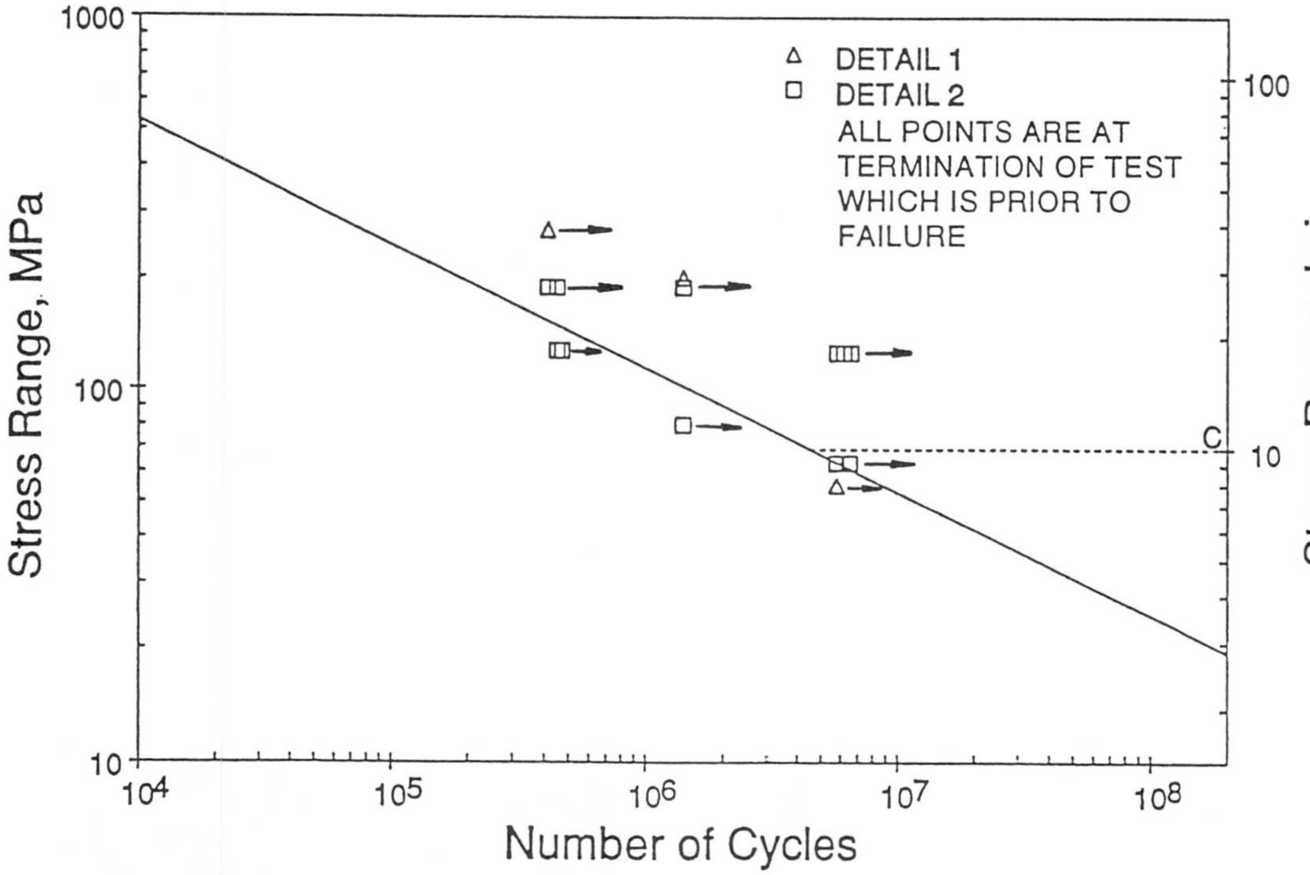

Figure 5: S-N data for cracks at the full-penetration connection detail plotted with theoretical life (Category C). Notes: 1) Detail 1 is cracking in the centerbeam at the connection (as shown in Figure 3) while detail 2 is cracking in the support bar at the connection. 2) The specimens had not actually "failed" and the cracks were still growing at the number of cycles indicated.