Field Measurements of Large Modular Expansion Joint

Charles W. Roeder, *University of Washington, Seattle*
Mark Hildahl, *David Goodyear Engineering Services*
John A. Van Lund, *Department of Transportation*

Modular expansion joints are sometimes used on bridges with large movement potential. Single-support-bar modular expansion joints with 1200 mm of movement capability were used at each end of the third Lake Washington Bridge between Seattle and Mercer Island on Interstate 90. Fatigue cracks were observed in these joints within the first few years of service, and an extensive research program was undertaken. An initial study used a range of analyses, which showed that the behavior of the joint was influenced by the dynamic wheel loading and the characteristics of the joint. Field measurements were performed to verify the analytical conclusions, and the results are summarized. The field measurements included measurements of strains, bending moments, and deflections for a series of controlled truck loadings on a large modular joint. Braking and acceleration of vehicles produce the largest horizontal wheel forces and joint movement. The horizontal forces produced by overrolling (nonbraking and nonaccelerating vehicles) are small. Impact and rebound due to vertical loading are significant. Measurements are compared with fatigue design recommendations and correlated with analytical results. Recommended vertical and horizontal fatigue design loads are given for large-movement single-support-bar expansion joints.

Modular expansion joints are used on bridges with large movements, and fatigue cracks have been noted on these systems. At present there is no specific AASHTO fatigue design procedure for modular joints; however, a relatively simple procedure has been proposed by Tschemmernegg and colleagues (*1–3*). The nominal stress range, $\Delta\sigma_{max}$, at critical locations in the joint components are computed for the fatigue design wheel loads, including impact. These fatigue design loads (gravity load of +91.0 kN, vertical rebound of −27.3 kN, and horizontal load of ±18.2 kN in either direction, all including impact) are based on field measurements on modular joints in Europe (*3*).

Recent research (*4–6*) has suggested that although the Tschemmernegg fatigue design method is easy to use and complete, it may not accurately represent the fatigue behavior of all modular joints because of their widely varying dynamic properties and stiffness characteristics. Single-support-bar modular expansion joints with 1200 mm of movement capability were used at each end of the third Lake Washington Bridge between Seattle and Mercer Island on Interstate 90 (*7*). Fatigue cracks were observed in these joints within the first few years of service. Figure 1 is a photograph of one of these cracks.

The joints (Figure 2 and 3) use a single transverse beam or support bar that supports all of the center-

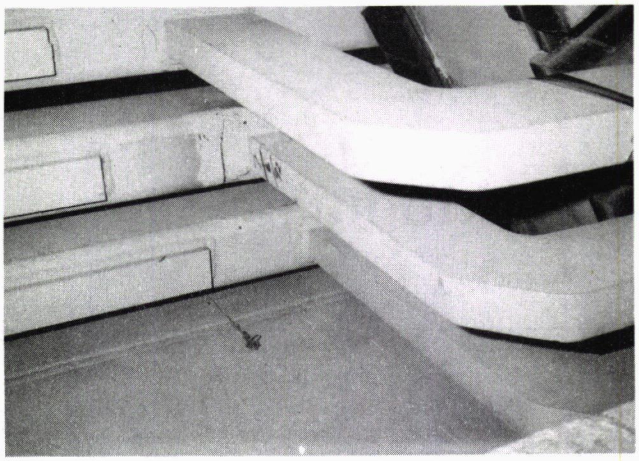

FIGURE 1 Fatigue cracking.

beams at each point. The support bar is a stiff, strong steel section, which is pinned at one end of the bridge superstructure, whereas it slides on a low-friction sliding surface at the other end. Elastomeric bearings are used to help cushion components of the joint and assist in the accommodation of movement and the control of spacing and geometry of joint components. The centerbeams must have a moveable attachment with stirrups, elastomeric springs, and low-friction sliders between the centerbeam and support bar.

Experimental Program and Measurements

An experimental study was started to examine the behavior of modular joints and to correlate this measured behavior to the prior analytical study (*4*). The large modular expansion joint at the east end of the high-occupancy vehicle (HOV) reversible lanes of the I-90 third Lake Washington Floating Bridge were instrumented (*5*) during the summer of 1993. The general objectives of the measurements were to

1. Verify the results of the earlier (*4*) computer analysis.
2. Verify the dynamic characteristics of the modular joint system including impact and damping.
3. Determine the stresses and strains of critical joint components under the applied loads.

Two types of instrumentation were used on this joint. The first type of instrumentation included eight groups of four strain gauges that were connected as full Wheatstone bridges to measure bending. All eight bending measurements were placed at various positions under the outside southernmost lane of traffic (Figure 4). Six of these channels measured bending in the vertical load plane, but two measured bending in the horizontal load plane. Six of the bending gauge groups (four vertical and two horizontal) were located on centerbeam CB13, which was the second centerbeam from the east edge of the joint. The remaining two bending groups were at-

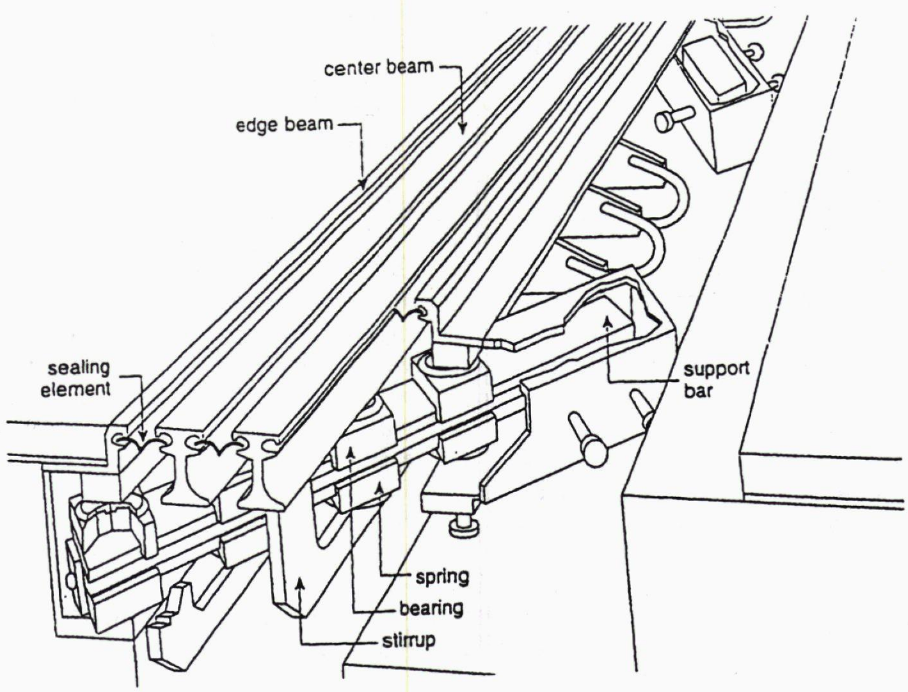

FIGURE 2 Single-support-bar system.

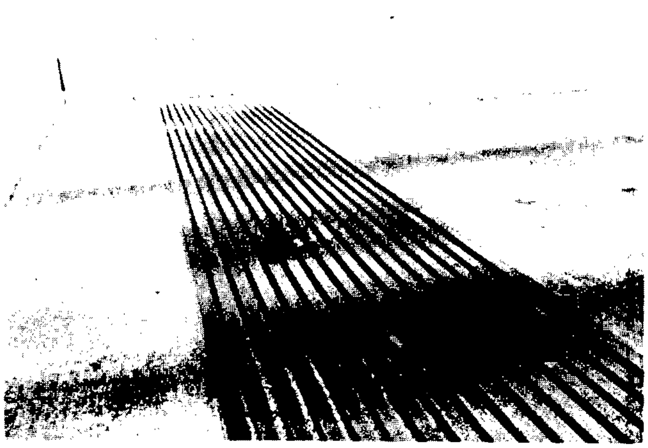

FIGURE 3 Road surface of modular expansion joint.

tached to adjacent centerbeams, centerbeams CB12 and CB14. Comparison of the bending moments measured in CB12, CB13, and CB14 gave a measure of the wheel load distribution between centerbeams as a function of time. The four vertical gauges on CB13 provided a redundancy of measurements so that the magnitude of the truck wheel load and the position of the truck could be estimated with the aid of influence lines for the measurement locations. The instrumentation also included two linear variable differential transformers that were used to measure the horizontal displacements of the centerbeams. The horizontal displacements were measured at the center of a long span and at the adjacent support bar of CB13. These horizontal displacement measurements approximately coincided with two of the more critical bending moment measurements.

All measurements were recorded as voltage differentials. For bending moments the voltage measurements were multiplied by a calibration factor to obtain curvature, and the curvature was multiplied by the stiffness to obtain the bending moment. Deflections were directly determined by multiplying the calibration factor by the voltage. The six bending channels of centerbeam CB13 were measured for nearly all of the controlled and uncontrolled field tests. The horizontal displacements and the bending channels on CB12 and CB14 were measured only for selective measurements during the controlled tests. HP5813A waveform recorders were used to record most of the data, and additional data were recorded with an HP3852A data acquisition system. The waveform recorders are capable of recording up to 4,000,000 samples per second of data per channel, but they are sampling at the rate of 2,000 samples per second for these tests since this was more than ample to measure the joint response. The recorders were coupled together, and they were self-triggering and continually sampled data. They only recorded data when a big enough measurement was noted, and then only a short burst (approximately 2 sec) of data was recorded. Data for a number of trucks were recorded in this manner until the internal memory was full. The data were then transferred to an HP9816 computer and stored in a compact binary format in an IEM 5300 disk drive. The data were transferred again by an HPUX 700-340 computer and were analyzed by the normal research computer facilities.

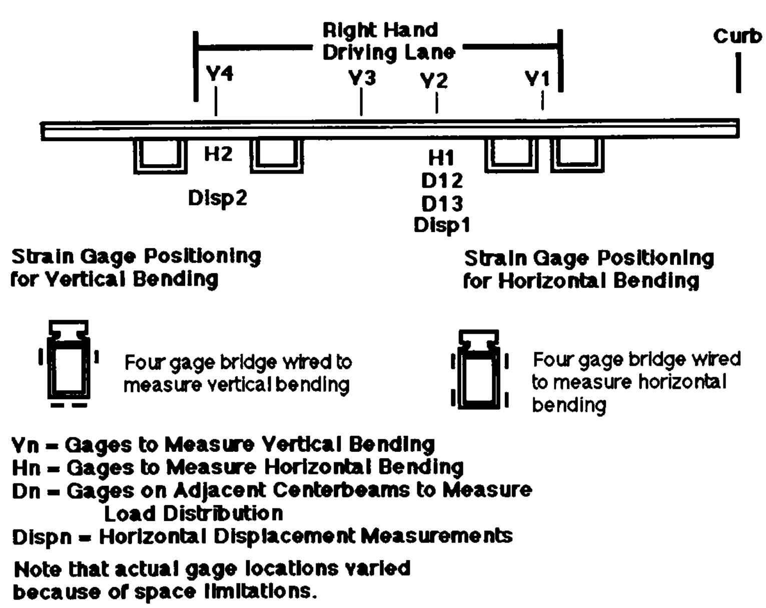

FIGURE 4 Instrumentation on expansion joint.

Test Program

Two series of controlled tests were performed (*5,6*). During August 17 to 19, 1993, the right lane of traffic was shut down for several hours each day, and loads were applied by a moderately heavy, three-axle dump truck. The dimensions and the static wheel loads of the truck were measured before testing. Figure 5 shows the static wheel loads and dimensions of the test truck. The truck passed over the joint at known speeds and locations 24 different times during the 2-day period. The position of the vehicle relative to the joint was measured by the tire track observed on strategically placed tape markers on the joint. The truck was at constant speed, braking, accelerating, or at rest. A second series of controlled tests was performed during February 1 and 2, 1994. This second series of controlled tests was performed when the bridge was closed to other traffic. This allowed many more options in the speed and placement of the vehicle on the joint. Forty-two load passes were made with the same truck and loading used in the earlier tests. Nearly all of the truck passes were made at various points within the outside (southernmost) lane. Most of the tests were performed with eastbound truck traffic, but a few passes were performed with a westbound truck. Two tests were performed with the truck passing in the center lane so that the effect of such a truck passing on the measured results could be determined. The results of these tests were used to establish basic elements of joint behavior such as the effect of truck position, truck braking or acceleration, and distribution of load between centerbeams.

Test Results

Figure 6 shows the typical measured bending moments due to the controlled test truck passing over the joint with nearly the same path very slowly and at 90 km/hr. The trucks were maintaining a constant speed with no vehicle braking or acceleration. The dynamic load experienced by the centerbeam is proportional to the maximum bending moment. Comparison of the two truck crossings shows that there is 30 to 45 percent amplification of the vertical loads (and moments) for the high-speed vehicle over that for the static loading. This measured amplification is typical of other values obtained at similar vehicle speeds. Figure 6 shows that a peak centerbeam bending moment is achieved as the wheel crosses directly over the centerbeam and a dynamic rebound occurs as the wheel leaves the centerbeam. Tschemmernegg (*1,2*) uses fatigue design loads that imply a dynamic rebound that is 30 percent of the maximum direct load on the joint. Rebound on the order of 30 to 50 percent of the direct-impact loading was noted with the truck traveling at 90 km/hr. There is no rebound, however, with the static loading, and this suggests that the rebound effect is smaller with slower-moving vehicles.

After the wheel leaves the centerbeam the centerbeam tends to vibrate in a mode of free vibration. Examination of the period of this vibration gives a measure of the period of the excited mode of vibration, and the free vibration response illustrated in Figure 6 suggests that the period of the centerbeam vibration is approximately 0.015 sec. Prior computer analyses (*4,5*) showed that many closely spaced modes of vibration contributed to the dynamic responses of these joints in both the horizontal and the vertical planes. The computed periods ranged from 0.05 to 0.005 sec, with 0.015 sec being an approximate average value. Thus, it appears that the measured period for vertical vibration of the centerbeam is consistent with that predicted in the theoretical calculations. Furthermore, it can be noted that the duration of loading on an individual centerbeam with the truck traveling at 90 km/hr is approximately 0.0125 sec. The ratio of this duration to the period of vibration is approximately 0.85, and the theoretical dynamic amplification predicted is approximately 50 percent. These combined observations suggest that there is a good correlation between earlier (*4–6*) theoretical predictions and experimental measurements. The decay of the free vibration after the rebound cycle can be used to estimate the damping in the joint, and damping on the order of 6 to 13 percent of critical was noted for trucks crossing the joint without significant acceleration or braking. A comparison of theoretical and measured dynamic characteristics is shown in Table 1.

Figure 7 shows the horizontal plane bending moments measured with the same trucks used to obtain the data given in Figure 6. The vehicle is crossing the joint at constant speed. However, it should be noted that the joint is on a slight 2 to 3 percent grade, and this grade requires some minimal acceleration to maintain constant driving speed. The bending moments again are theoretically proportional to the dynamic force felt by the centerbeam. Earlier dynamic analyses (*4,5*) suggested that this joint system would be very flexible in horizontal loading, and as a result it was postulated that the centerbeam could not experience a large horizontal load. On the other hand, the Tschemmernegg fatigue evaluation procedure (*1–3*) requires a horizontal design force that is approximately 30 percent of the basic vertical (static) design force, and the method also postulates that the elastic support points be modeled as rigid connection for the horizontal loading. Comparison of the moments in Figure 7 with those shown in Figure 6 suggest that the dynamic force acting in the horizontal direction is approximately 10 percent of the vertical load.

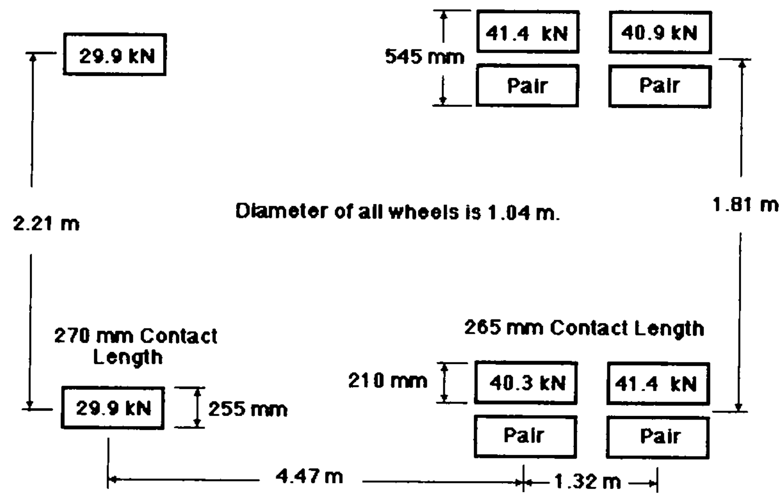

FIGURE 5 Wheel loads and geometry of test truck.

Figure 8 shows a typical comparison with the data in Figure 7 with the truck traveling at a slower speed (approximately 50 km/hr). The dynamic amplification is in the range of 25 to 35 percent of the static load for this reduced speed. The duration of loading is longer at this reduced speed, and the ratio of the duration to the period of vibration for the centerbeam is also proportionally larger (1.55 as opposed to 0.85). The dynamic rebound is on the order of 40 to 50 percent of the vertical load at 90 km/hr, approximately half this amount at 50 km/hr, and zero when the vehicle is at rest.

Figure 9 shows the horizontal bending moments for the truck crossing for which data are given in Figure 8. Comparison of Figures 7 and 9 shows that the horizontal force of the vehicle traveling at 50 km/hr is somewhat larger than that noted for the vehicle traveling at 90 km/hr. However, in both cases the bending moment and horizontal force are much smaller than the vertical load. The majority of the participating masses in the horizontal modes of vibration were resident in modes with periods in the range of between 0.16 and 0.035 sec. Therefore, the ratio of the duration of load to the period varies between a high of approximately 0.6 when the vehicle is traveling at 50 km/hr and a possible low of 0.3 to 0.0 when the vehicle is traveling at 90 km/hr.

The horizontal loads are much smaller than suggested by the Tschemmernegg fatigue design procedure

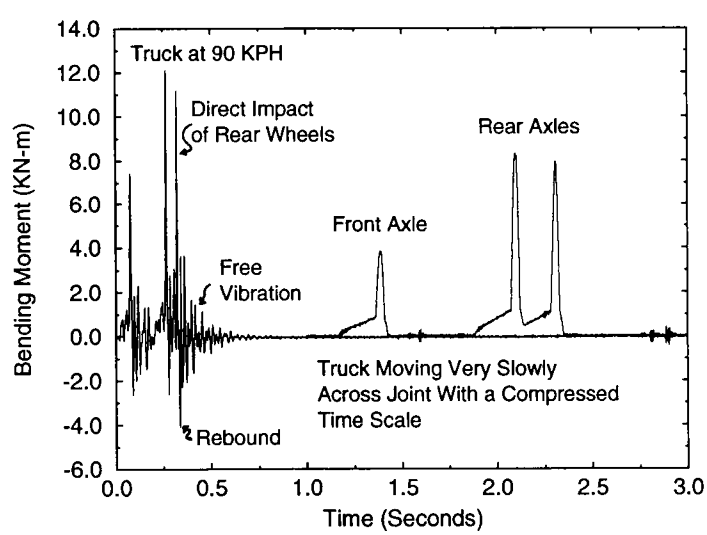

FIGURE 6 Measured bending moment in centerbeam due to vertical wheel loads at 90 km/hr and static conditions.

TABLE 1 Typical and Measured Dynamic Characteristics

Dynamic Characteristics	Estimated From Field Measurements	Estimated from Past Theoretical Calculations	Tschemmernegg Estimates from Field Measurements
Periods for Vertical Modes of Vibration	0.0125 to 0.015 seconds for Normal Vibration	0.005 to 0.05 secs. with Averages Approx. 0.015 seconds	Approx. 0.015 secs.
Periods for Horizontal Modes of Vibration	0.03 to 0.05 seconds for Normal Vibration and 0.12 seconds for severe braking	0.015 to 0.15 secs with Average Approx. 0.03 to 0.05 seconds and 0.15 secs associated with global movements	Approx 0.048 secs.
Damping	6 to 13% of Critical Under Normal Vibration	No Estimate	Approx. 7.1 %

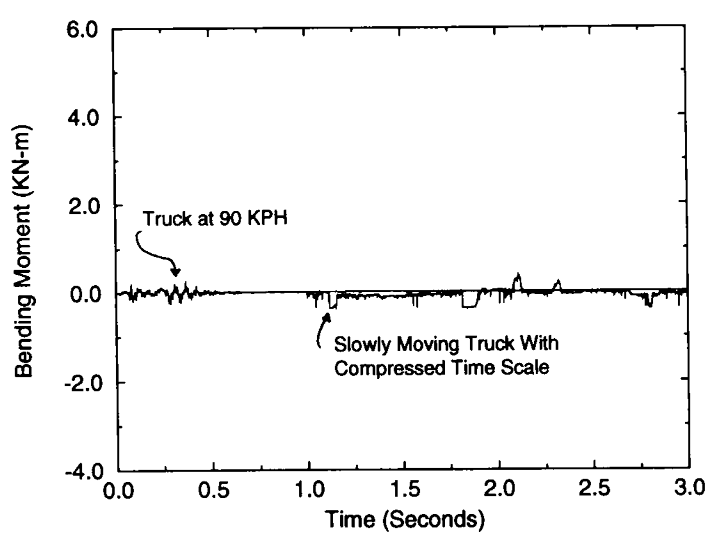

FIGURE 7 Measured bending moment in centerbeam due to horizontal wheel loads at 90 km/hr and static conditions.

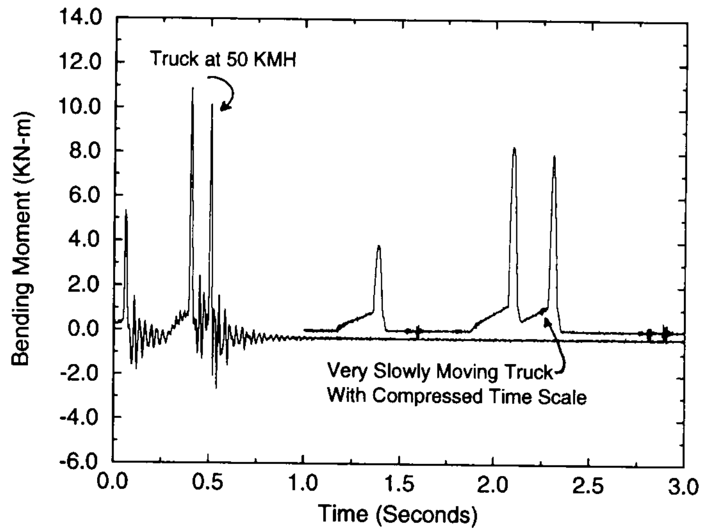

FIGURE 8 Measured bending moment in centerbeam due to vertical wheel loads at 50 km/hr and static conditions.

under normal driving conditions. If the vehicle is braking or accelerating as it crosses the modular joint, the horizontal forces are much larger. Figure 10 shows the moments due to horizontal loading with emergency braking for a vehicle originally traveling at 90 km/hr. Comparison of Figures 7, 9, and 10 shows that vehicle braking causes much larger horizontal dynamic loads. These dynamic loads due to braking may be even larger than those suggested by Tschemmernegg (*1–3*).

Horizontal movements were also measured for some cases. No horizontal movement of the centerbeam was noted if the truck was not braking or accelerating to gain speed over the joint. However, Figure 11 shows typical centerbeam movement if the truck is braking to an emergency stop. It can be seen that a substantial horizontal deflection occurs under this severe braking condition. The maximum movement is approximately 10 mm, and there is a permanent set of approximately 3 mm. The largest centerbeam movements appeared to occur at slower speeds because of the dynamic characteristics of the joint. This is consistent with the observations made in an analysis that greater dynamic amplification of horizontal loads occurred at slower speeds because the duration of loading more closely matches

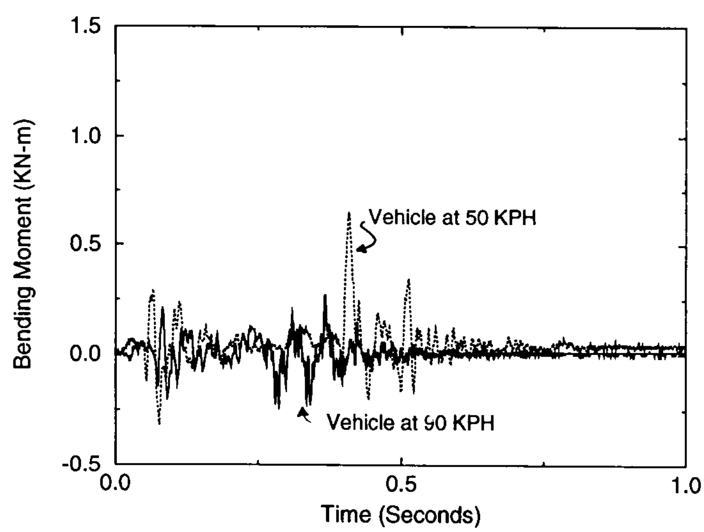

FIGURE 9 Measured bending moment in centerbeam due to horizontal wheel loads at 50 and 90 km/hr.

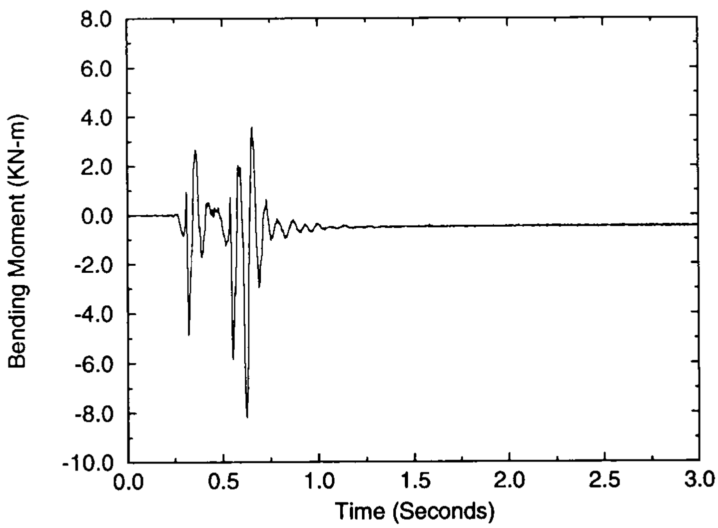

FIGURE 10 Measured bending moment in centerbeam due to horizontal wheel loads at 90 km/hr with emergency braking.

the longer periods noted for horizontal displacement. The major portion of the deflection is causing deformation and sliding of the elastomeric springs. That is, the centerbeam moves approximately as a rigid body. Some of the horizontal displacement is recovered after the load is removed, but that due to sliding results in permanent set and is not immediately recovered. The permanent set is recovered after time because of vibrations of the joint due to lighter traffic and the geometry of the joint system. These measurements indicate that horizontal loads on this particular joint system are significant only when the vehicle is braking or accelerating. This is consistent with some observations (*8*) of past joint fatigue behavior.

Design Implications

The results of the controlled tests performed in August and February were compared, and the results were similar except that it was noted that a given truck crossing on a specific path caused a larger centerbeam bending

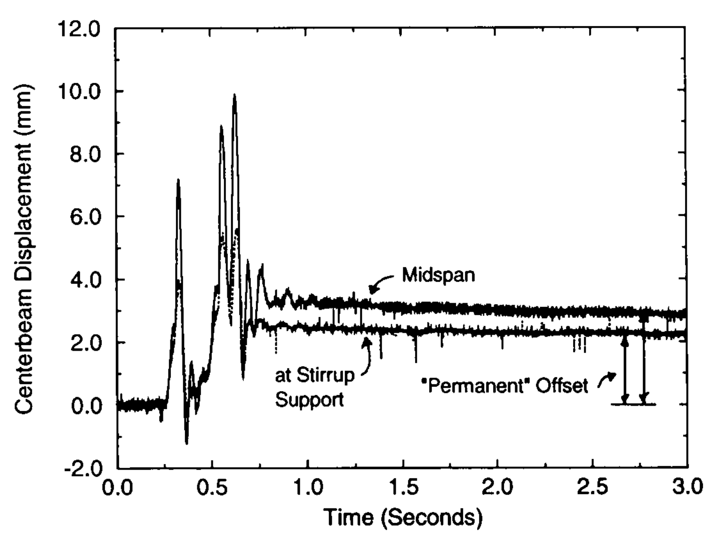

FIGURE 11 Measured horizontal displacement of centerbeam due to horizontal wheel loads at 90 km/hr with emergency braking.

moment in the tests in February than in the tests in August. The difference was small and clearly indicated that the data recorded during the two different time periods were comparable and permitted an evaluation of the load distribution between centerbeams. The joint geometry was measured, and the application of Tschemmernegg's graphical wheel distribution model suggested that less than 50 percent of the total wheel load should be applied to a single centerbeam in August and that 50 percent would be appropriate in February. Bending moments obtained for adjacent centerbeams, centerbeams CB12, CB13, and CB14, were compared to examine the load distributions between centerbeams. These measurements indicated that a larger portion of the vertical load was carried by an individual centerbeam than suggested by the Tschemmernegg method. For this joint system it appears that the load distribution to the most heavily loaded centerbeam should be increased by 10 percent over that recommended by the Tschemmernegg method.

An examination of the fatigue design load spectrum was another important goal of this research. The uncontrolled truck measurements provide insight into these load data when they were combined with the controlled test results. The dynamic responses of nearly 20,000 truck wheel crossings were measured during these uncontrolled tests, and summary data on the peak response for each wheel, the maximum rebound, and free vibration cycles were developed. However, the responses of only the very heaviest trucks were measured. That is, trucks with vertical dynamic wheel loads of less than approximately 30 kN were neglected. The Tschemmernegg load spectrum and statistical distribution (3) suggest that this limit includes only the heaviest 16 percent of the truck wheels.

The speed of the truck crossing the joint, the position of the truck on the joint, the geometry of the truck wheels, the distribution of loads between centerbeams, and the actual static wheel loads of the truck all affect the uncontrolled measurements. None of these variables are known with certainty for any one truck measurement. However, substantial information can be theoretically inferred (6) on the basis of comparison of the measured data with theoretical influence lines for each measurement location. Therefore, the data were analyzed to examine the effects of these different parameters. Measurement of typical truck axles indicate that a spacing of approximately 1.8 m is appropriate for most dual-wheel rear axles, and this was used in the design load evaluation since the largest wheel loads produce the greatest fatigue damage. Front wheels have larger and more variable wheel spacings, but the wheel loads are usually lighter.

Given the wheel spacing, the position of the truck crossing the joint and the magnitude of the dynamic load can be theoretically predicted from the influence lines generated for each measurement location. The controlled truck measurements were used to evaluate the location and load estimation procedure. There were enough measurements to provide redundancy and checks of the data evaluation. It was determined that some channels of data produced inherently more useful data than others. Furthermore, it was determined that there was relatively little sensitivity to position if the truck was near the middle of the travel lane. There was great sensitivity if it was changing lanes or was close to the curb. Finally, it was determined that vehicles that are outside the middle portion of the travel lane were identifiable, because of the ratios and relative magnitudes of critical measurements.

As a result data for crossings by trucks that were changing lanes or driving out of the right-hand lane were identified and removed from the statistical sample. The dynamic wheel loads were then estimated for direct-impact loading, vertical rebound, and horizontal loading with the vehicle in the middle portion of the lane. The most reliable channels of measured data were used to estimate the dynamic wheel load, and the average of these most reliable estimates was used. The dynamic wheel loads considered the distribution of load between centerbeams and the distribution of the wheel loads on the centerbeam. Figures 12 and 13 show the measured load spectra for vertical and horizontal wheel loads, respectively, from statistical analysis of the uncontrolled truck measurements compared with the Tschemmernegg design spectrum. Again, it should be emphasized that responses for only the heaviest 16 percent of truck traffic were measured in these tests. It can be seen that a substantial number of trucks exceeded the maximum vertical load in the Tschemmernegg design spectrum, but the maximum horizontal wheel loads achieved in this study were very similar to those reported by Tschemmernegg. There were a larger number of large vertical dynamic loads and fewer large horizontal dynamic loads than recommended by Tschemmernegg. These larger vertical loads cause the largest amount of fatigue damage. Thus, the Tschemmernegg load spectrum was viewed as unconservative for vertical loads and overly conservative for horizontal loads on this joint. It should be emphasized that these recommendations are joint specific. Different recommendations must be expected for other joint systems because of the variations in the dynamic characteristics of the joints. Therefore, it is recommended that the vertical dynamic wheel load for this joint system be increased to 110 kN. The vertical rebound load should be increased to 45 kN. When these increased vertical loads are used, it is appropriate to recognize the smaller horizontal loads present in the joint. Therefore, a horizontal load of 10 kN is suggested for this joint system and traffic pattern.

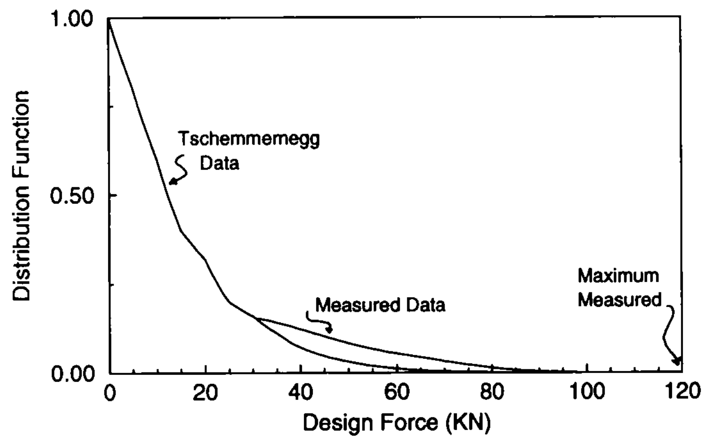

FIGURE 12 Cumulative distribution functions for vertical dynamic wheel loading.

These fatigue design load and load distribution recommendations are summarized in Table 2.

Summary and Conclusions

This paper has described a series of field measurements performed on a single-support-bar modular joint system under dynamic truck loading. The measurements were performed in response to fatigue cracks noted on the joint and a series of calculations completed after the first cracks were noted. The experimental methods and the results are summarized in this paper.

A few general conclusions can be noted:

1. The experimental observations appear to be consistent with earlier theoretical calculations (*4,5*). The dynamic periods measured in the experiments are consistent with the theoretical predictions.

2. The vertical loading due to the direct impact of the truck is amplified through a wide range of vehicle speeds, with dynamic amplification on the order of 50 percent expected at normal interstate vehicle driving speeds of 90 km/hr.

3. The vertical rebound load is larger with higher-speed vehicles and smaller with slower traffic.

4. The horizontal loads under ordinary traffic on this particular joint system are much smaller than those suggested by the Tschemmernegg fatigue design method. This occurs because of the horizontal flexibility and potential for slip noted with this type of modular joint. This supports the prior theoretical calculations that indicated that joint behavior is very dependent on the joint type. Horizontal forces are likely to be much more significant with some very stiff modular joint systems.

5. Bending moments due to horizontal loads under vehicle braking may be very large. These moments may

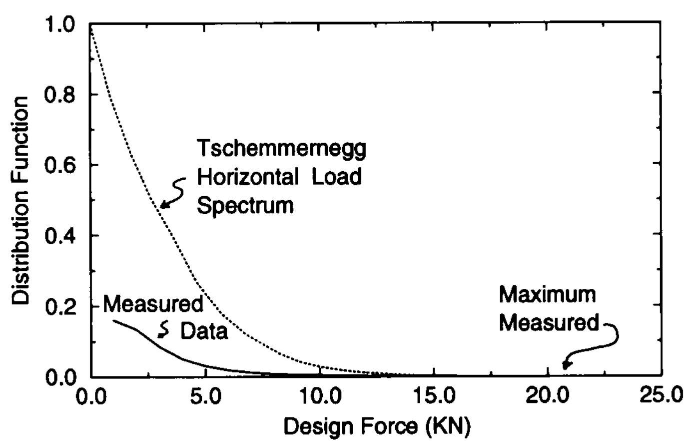

FIGURE 13 Cumulative distribution functions for horizontal dynamic wheel loading.

TABLE 2 Fatigue Design Load Recommendations

	Recommendations From This Research	Tschemmernegg Recommendations
Direct Vertical Dynamic Load	110 KN	91 KN
Rebound Vertical Dynamic Load	45 KN	27.3 KN
Positive Horizontal Dynamic Load	+10 KN	+18.2 KN
Negative Horizontal Dynamic Load	-10 KN	-18.2 KN
Load Distribution to Centerbeams	0.1 + Graphical Procedure	Graphical Procedure Provided

exceed those suggested by the Tschemmernegg fatigue design method. For this joint system horizontal movements occur in the joint when the braking vehicles cross the joint. The movements involve multiple spans of centerbeams accompanied by shear deformation of the elastomeric springs and sliding of the low-friction surfaces. The large moments are caused by the increased effective centerbeam span induced by support movement as well as by increased load.

6. Load distribution between centerbeams is also evaluated, and these measurements suggest that the load distribution between individual centerbeams produces a somewhat larger force on individual centerbeams than suggested by the Tschemmernegg fatigue evaluation method. Fatigue design loads are recommended for direct-impact, rebound, and horizontal loadings for this type of single-support-bar modular joint.

ACKNOWLEDGMENTS

This research was funded by the Washington State Transportation Center and the Washington State Department of Transportation. The assistance of John Van Lund, Myint M. Lwin, and Alan H. Walley is gratefully acknowledged.

REFERENCES

1. Pattis, A., and F. Tschemmernegg. *Fatigue Testing and Design of Modular Expansion Joints.* University of Innsbruck and The D. S. Brown Co., Innsbruck, Austria, March 1992.
2. Fatigue Design and Testing for Expansion Joints. *Technology Bulletin for Bridge Bearings, Expansion Joints and Components,* No. 1. The D. S. Brown Co., North Baltimore, Ohio, Oct. 1991, 2 pp.
3. Tschemmernegg, F. The Design of Modular Expansion Joints. *Joints and Sealants.* Vol. 1, preprint. *Proc., Third World Congress on Joint Sealing and Bearing Systems for Concrete Structures,* Toronto, American Concrete Institute, Detroit, Mich., Oct. 1991, pp. 67–86.
4. Roeder, C. W., M. Hildahl, and J. A. Van Lund. Fatigue Cracking in Modular Expansion Joints. In *Transportation Research Record 1460,* TRB, National Research Council, Washington, D.C., 1994.
5. Hildahl, M. *Fatigue Cracking of Modular Expansion Joints.* M.S. thesis. University of Washington, Seattle, 1993.
6. Roeder, C. W. *Field Measurements of Dynamic Wheel Loads on Modular Expansion Joints.* Report WA-RD 369.1. Washington State Transportation Center, Jan. 1995.
7. Brown, S., and U. Haerle. Design of a Sealed Expansion Joint for the 3rd Lake Washington Bridge. *Joint Sealing and Bearing Systems for Concrete Structures,* vol. 2, SP-94. American Concrete Institute, Detroit, Mich., 1986, pp. 967–974.
8. Mayrbaurl, R. M. Analysis of the Manhattan Bridge Modular Expansion Joints. Presented at 73rd Annual Meeting of the Transportation Research Board, Washington, D.C., Jan. 1994.

The opinions and conclusions expressed or implied in this paper are those of the authors and are not necessarily those of the funding agency.