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16. ABSTRACT

Modular expansion joints are frequently used on bridges with large movements, and fatigue cracking has been noted on a number of these joints. Past studies have examined fatigue design procedures and theoretically predicted joint behavior under traffic loading. These studies have shown that the dynamic characteristics of these joints are variable, and the fatigue design loads must vary with the joint characteristics. This research report describes a field investigation of the dynamic loads and behavior of a swivel joist modular joint system. The study was performed to verify the response predicted in past theoretical studies, to establish the dynamic characteristics of the joint, and to determine appropriate fatigue design loads on the joint. The measurements are described and analyzed in detail. The report develops important conclusions regarding the dynamic loads on the joint, the distribution of load between elements of the joint, and the relative importance of different load components. The subject joint was shown to be more sensitive to vertical loads and less sensitive to horizontal loads than suggested by existing fatigue design methods. Traffic patterns were shown to have a significant impact on the behavior of this joint system. The report includes fatigue design recommendations.

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Final Research Report
Research Project T9233, Task 46
Modular Expansion Joints - Loading Measurements

FIELD MEASUREMENTS OF DYNAMIC WHEEL LOADS ON MODULAR EXPANSION JOINTS

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DISCLAIMER

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SUMMARY

Modular expansion joints are frequently used on bridges that have movement requirements of greater than 125 mm (5 inches). Fatigue cracking has been noted on these joints. Tschemmernegg has developed a design procedure to deal with the fatigue problem. However, recent analytical studies have shown that the dynamic characteristics of these joints are quite variable, and the dynamic response will vary with these joint characteristics. This variability limits the effectiveness of the existing fatigue design procedure on some joint systems. This study was a field investigation of the dynamic loads and behavior of the swivel joist modular joint system on the 3rd Lake Washington floating bridge. The study was performed to verify the response predicted in past theoretical studies, to establish the dynamic characteristics of the joint, and to determine appropriate fatigue design loads on the joint.

The modular joint was instrumented, and measurements of strains, curvature, and deflection were conducted with trucks of known weight and driving conditions and with normal, uncontrolled traffic. The procedures are described in the body of the report. The measurements were analyzed to determine bending moment, stress, and dynamic vehicle wheel loading. These results were compared to past theoretical studies and fatigue design procedures. Conclusions regarding the dynamic loads on the joint, the distribution of load between elements of the joint, and the relative importance of different load components were developed. The study found that the subject joint was more sensitive to vertical loads and less sensitive to horizontal loads than suggested by the Tschemmernegg method. It also found that changes in traffic patterns have a significant impact on the behavior of this joint system. Fatigue design recommendations are made within the report.

INTRODUCTION

RESEARCH OBJECTIVES

A previous research study for the Washington State Department of Transportation (WSDOT) examined fatigue cracking noted on the expansion joints of the 3rd Lake Washington floating bridge (Br. No. 90/25N). This investigation was an analytical study, and it raised some important questions regarding the actual field conditions that caused the fatigue cracking. Field measurements of the expansion joints were needed to

- verify the results of the computer analysis and the conclusions drawn from this analysis
- determine the load spectrum for vertical loads for design and replacement of the joints, since computer analysis suggested that the flexibility of the elastomeric springs resulted in longer periods and more amplification of the vertical loads than those suggested by the Tschemmernegg method
- determine the load spectrum for horizontal loads for design and replacement of the joints, since computer analysis suggested that the flexibility introduced by the elastomeric springs resulted in attenuation of the horizontal loads on the joint
- verify the dynamic characteristics of the joint, including impact and damping.

THE PROBLEM

The WSDOT commonly uses modular expansion joints on bridges whose expected movements are larger than 127 mm (5 inches). Modular joints with a total movement capacity of 1200 mm (48 inches) were manufactured by The D.S. Brown Company under license of the Maurer Sohne Company of Munich, Germany, and were installed on the third Lake Washington bridge. These expansion joints, first subjected to traffic in 1989,

are believed to be the largest modular expansion joints in the world. The design is a fairly standard, single support bar system, except that steel tubes with an extruded rail cap were substituted for the heavy center beams because of Buy American requirements for federally funded bridge construction.

Approximately 6 months after the bridge was opened to traffic, WSDOT received numerous complaints because the expansion joints were noisy. Inspection of the joints showed that the elastomeric bearings used to cushion the traffic impact between the center beams, stirrups, and support bars were loose. Shims were added, but within a year cracks in the center beams were noted. Most of these cracks started at the toe of the stirrup fillet weld and progressed through the center beam, as shown in Figure 1. Two attempts to repair these cracks were made, but with little success. To date, approximately 25 fatigue cracks have been noted.

WSDOT had a number of concerns regarding this fatigue cracking, and an earlier study (Roeder, 1993 and Roeder, Hildahl, Van Lund, 1994) analyzed the issue in some detail. This earlier study provided extensive computer analysis of the joint, and it examined existing fatigue evaluation procedures. Correlation of these two factors suggested that several serious discrepancies existed between existing fatigue evaluation and design procedures and the behavior computed for these joints. In particular, the study suggested that the fatigue design loads used in the Tschemmernegg procedure did not necessarily reflect the type of loading expecting on the subject modular joint. Further, the S-N curve developed for the subject modular joint did not appear to reflect the observed fatigue cracking history. As a result of these and other similar concerns, field measurements were undertaken to determine the actual field conditions and behavior of the larger modular joints on the 3rd Lake Washington bridge.

Figure 1. Photo of a Fatigue Crack on the 3rd Lake Washington floating bridge

REVIEW OF PREVIOUS WORK

EXISTING FATIGUE EVALUATION PROCEDURES

Existing fatigue evaluation procedures are summarized briefly here but were described in detail in an earlier report (Roeder, 1993). Tschemmernegg developed the first complete fatigue design procedure for modular expansion joints. This evaluation procedure (Tschemmernegg, 1988; Pattis and Tschemmernegg, 1992; D.S. Brown, 1991; Tschemmernegg, 1991) is a relatively simple procedure.

First, the loads on the expansion joint are determined. These loads include a vertical component attributable to the dynamic response caused by gravity load and a horizontal component attributable to traffic acceleration, braking, and rebound forces. The recommended wheel loads, including impact, are vertical loads of a maximum of +91 kN (+20,450 lbs) and minimum of -27.3 kN (-6,100 lbs), and a horizontal force of $\pm$ 18.2 kN ($\pm$ 4,100 lbs).

Second, the stresses in the center beams and support bars are calculated to determine the maximum computed stress range, s_{smax}. The centerbeams are treated as continuous beams, and the elastic parts of the expansion device are treated as rigid supports for determining of the moments and the stress level. For normal conditions, each centerbeam is assumed to carry 50 to 60 percent of the wheel load with the wheel spacing at 1.8 m (6 ft), since the wheel distributes the load to more than one center beam.

Third, this maximum stress range is compared to an S-N curve developed from experimental results by the simple equation

$$\frac{s_{smax}}{2} < s_{sL} \, . \qquad \text{(Eq. 1)}$$

The comparison considers the full load history of trucks on the modular joint and the accumulation of damage attributable to variable amplitude loading through the application of partial safety factors. Separate S-N curves are provided for each component

of the joint. The endurance limit, s_{SL}, is intended to be the stress level that can develop 100 million cycles of loading, but it is inferred from an interpretation of experiments performed at stress ranges with fatigue lives of less than 2 million cycles. The slope of the log-log S-N curve is assumed to be -0.33 for a stress range of less than 5 million cycles and -0.2 for a stress range of between 5 million and 100 million cycles, as illustrated in Figure 2. The intercept at 100 million cycles is accepted as the endurance limit.

The Tschemmernegg procedure has been used for the fatigue design of a few modular joints in the U.S., but at present there is no AASHTO fatigue design procedure applicable to modular joints. The NCHRP 12-40 Research Program, Fatigue Criteria for Modular Bridge Expansion Joints, has recently started, and a major objective of this research program is the development of a fatigue evaluation procedure for these joints. However, at present no results from this study have been published.

EXISTING FIELD DATA

Tschemmernegg also has provided much of the field measurement data for modular expansion joints (Pattis and Tschemmernegg, 1991; Tschemmernegg, 1973). These measurements were used as a basis for developing his fatigue design procedure. The earliest measurements (Tschemmernegg, 1973) were performed on a modular joint built with a very stiff mechanical system, as illustrated in Figure 3. The measurements showed that the loads experienced by the joint components and system are dynamic loads, which depend upon the dynamic characteristics of the joint and the loading. These loads are really a dynamic response rather than a simple truck wheel load. The loads are time dependent, and he considered factors such as the eccentricity caused by edge loading as the wheel progresses across the surface of the centerbeam rail, horizontal loads caused by braking and acceleration of vehicles, and loads caused by a sloped driving surface. These early measurements were primarily force measurements made with instrumented and calibrated

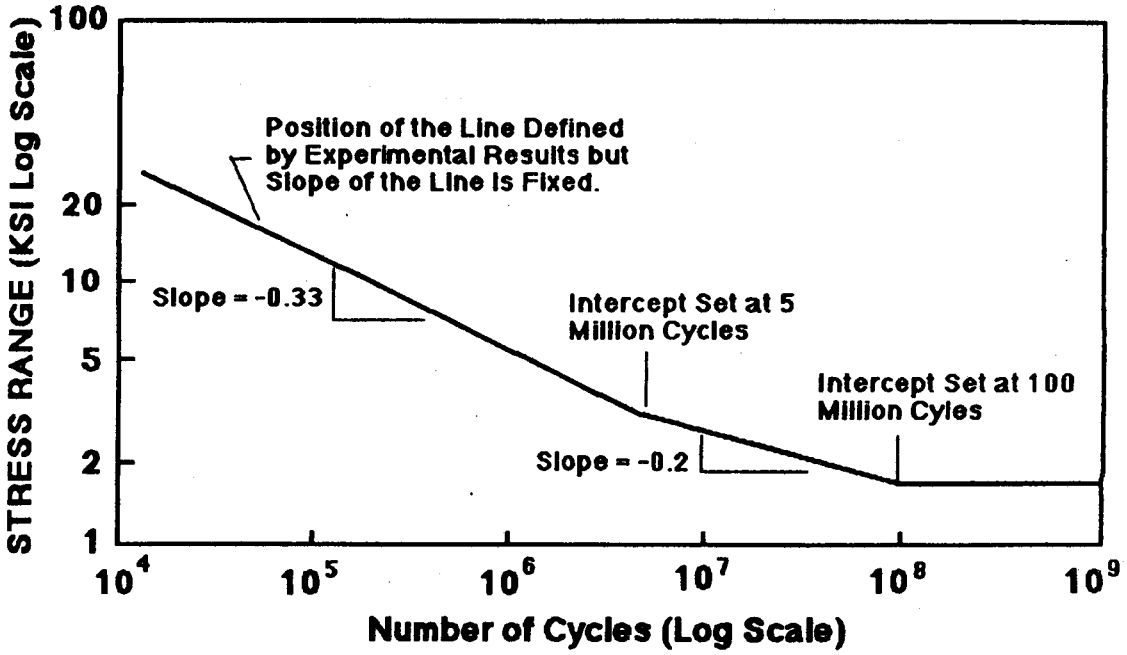

Figure 2. S-N Curve Construction for the Tschemmernegg Fatigue Design Procedure

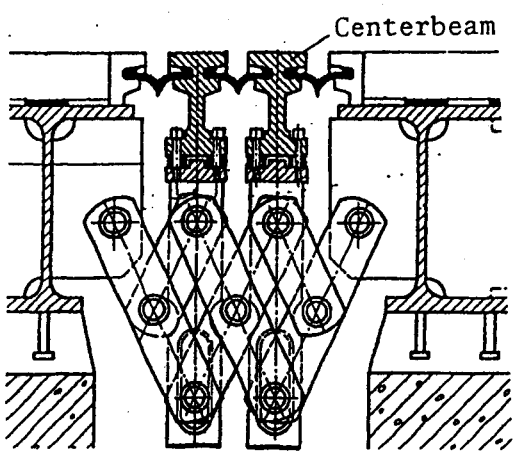

Figure 3. Stiff Mechanical Support System Used in the Rheinstahl Joint System and Considered in Early Field Measurements

bolts used to attach the centerbeam to the support mechanism. The measurements were taken under controlled truck conditions in which the weight, velocity, and driving conditions were known, and a series of measurements of normal, uncontrolled truck traffic were conducted. These uncontrolled measurements led to the statistical load spectrum shown in Figure 4. The spectrum shown in this figure was taken from Tschemmernegg's 1973 paper and was based on measurements taken on the Neheim-Husten Bridge on national highway 7 in Germany.

More recently, Tschemmernegg and Pattis (1991), Ostermann (1991), and Braun (1992) made additional field measurements of modular joint behavior. These measurements included joints with multiple and single support bar systems, and they included systems with some elastic flexibility attributable to elastomeric bearings in the support mechanism or sliding potential attributable to PTFE sliding elements in the joint. In these later tests, measurements of strain, loading, and horizontal displacements were performed. Braun reported that the horizontal displacement of the centerbeams developed a spectrum such as that shown in Figure 5. The fatigue design procedure has been modified (D.S. Brown, 1991; Tschemmernegg, 1991) to include this additional information. However, it is important to note that the load spectrum shown in Figure 4 has not changed significantly with this new information. Figure 5 suggests that the horizontal displacements are relatively small under normal traffic loading, and so the researchers have postulated that the elastic and sliding supports are effectively rigid under dynamic loading. They further suggest that it is conservative to design for a rigid support, since the bending moments and bending stresses are larger with rigid supports than with flexible supports. The net effect of this practice is that the load spectrum is proposed for all types of modular expansion joint, even though engineers recognize that the joint loading is dependent upon the dynamic characteristics of the joint and that joint characteristics vary widely.

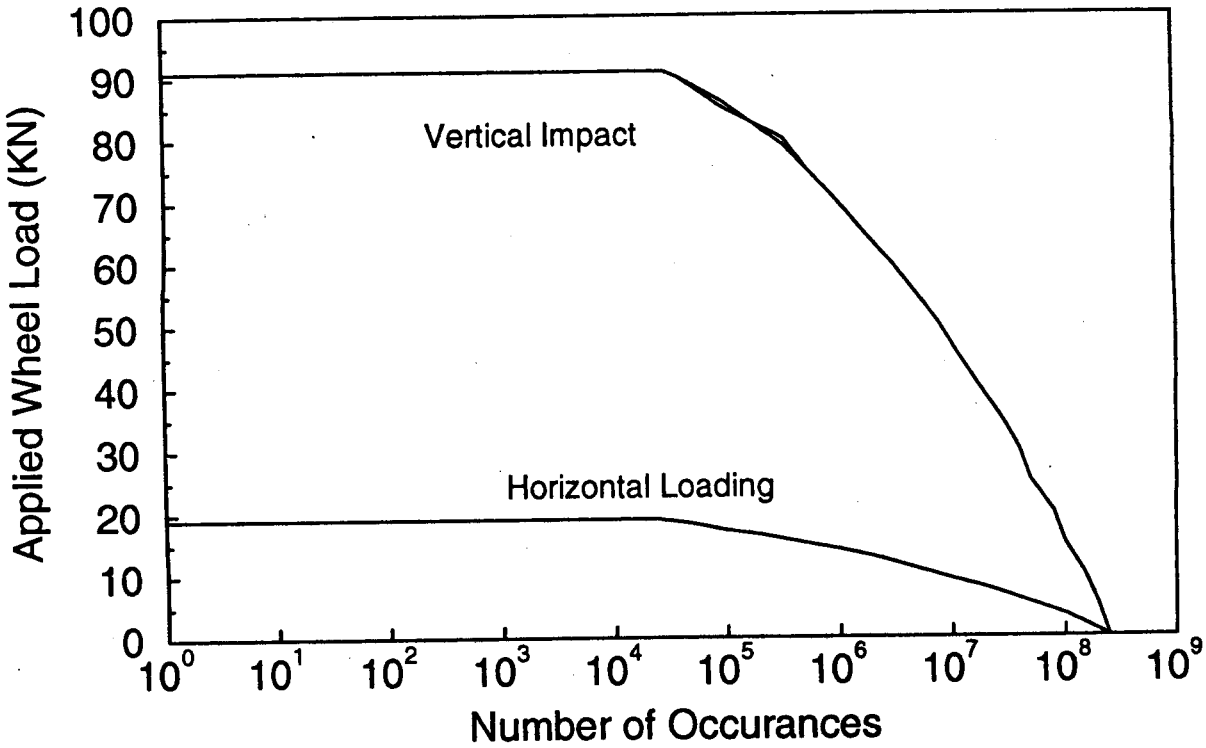

Figure 4. Horizontal and Vertical Load Spectrum Proposed by Tschemmernegg
{Fig. 8 of [Tschemmernegg, 1973]}

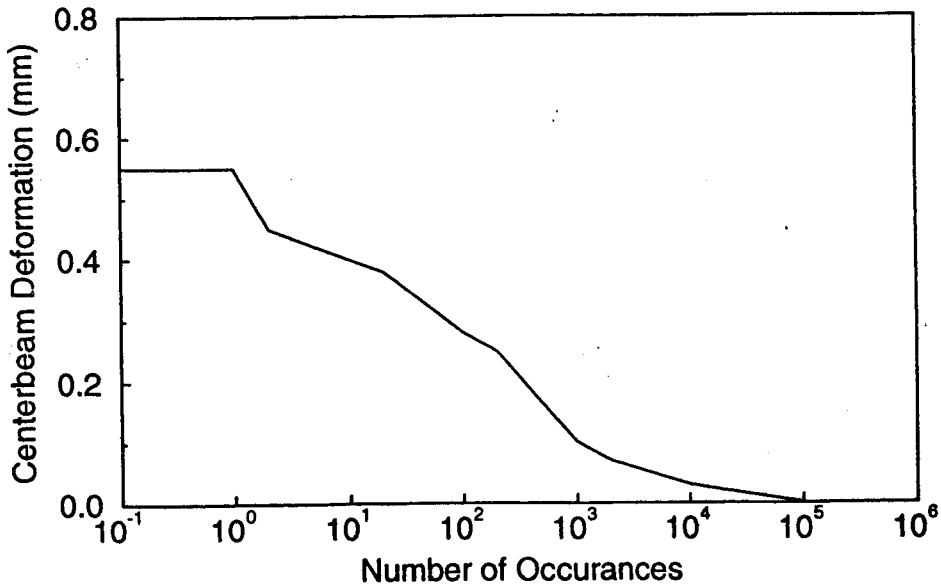

Figure 5. Spectrum of Horizontal Deflections Obtained by Braun
{Fig. 10 of [Braun, 1992]}

The spectrum shown in Figure 4 is used in the Tschemmernegg design method. However, it is not used directly. Instead, an arbitrary magnitude of force for vertical and horizontal loads, including direct loading and rebound, are employed. The statistical variation is included through the partial safety factors used to apply the variable amplitude fatigue calculations, and is ultimately included in the simple stress check used in Equation 1.

Others (Koster, 1986) have taken exception to the load spectrum used in the Tschemmernegg fatigue design procedure. Koster contends that deformability of the joint is desirable because it may spread the load and possibly reduce the critical fatigue stress. This latter position is logical, but the elastic deformation and stress distribution are very complicated in a modular joint system. Agarwal (1991) recently performed a series of field measurements on a modular joint on a bridge in Canada. His field measurements suggested that the loads and load spectrum used in the Tschemmernegg procedure may not be universally applicable to all modular joints. He did not detect the large horizontal forces proposed by the Tschemmernegg design spectrum. However, it was not clear whether the instrumentation had sufficient sensitivity to detect the true loads on the joint.

OTHER PRIOR INVESTIGATIONS

An earlier study (Roeder, 1993; Roeder, Hildahl, Van Lund, 1994) investigated the fatigue problems for the 1200 mm modular joints on the 3rd Lake Washington bridge. This study was an analytical study that examined the predicted behavior of the joints and attempted to correlate these predictions to existing design procedures and prior research results. A number of conclusions resulted from this study. First, the dynamic behavior of each type of modular joint system is strongly influenced by the dynamic response of that system. The periods of vibration for both vertical and horizontal modes of vibration were computed for the single support bar expansion joint used on the 3rd Lake Washington bridge. Figure 6 shows the theoretical amplification that would be expected for these joint

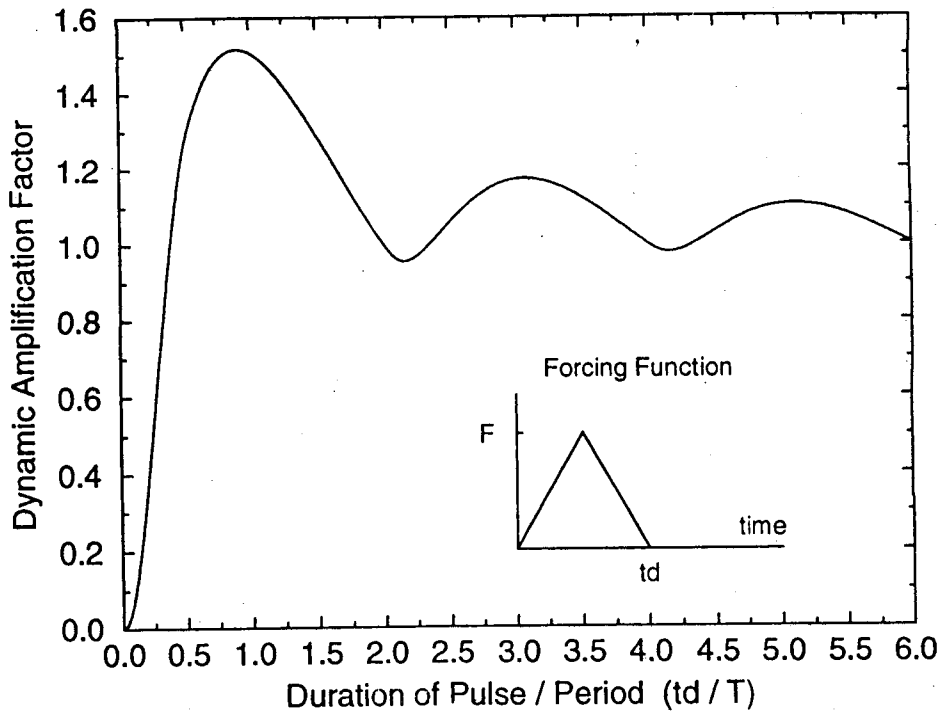

Figure 6. Theoretical Dynamic Amplification for a Ramp Function Loading

components under dynamic wheel loading. These periods suggested that the joint amplifies horizontal loads that are applied slowly. It may attenuate many other horizontal load effects, but it amplifies vertical loads through a wide range of vehicle speeds. The vertical modes of vibration with significant participating mass had periods that ranged from 0.05 to 0.005 seconds. These observations suggested a quite different fatigue load design spectrum than that given in Figure 3. Single support bar expansion joints may not experience the large horizontal or lateral loads proposed by the Tschemmernegg procedure because of the transverse flexibility of the joint.

Wheel loads cause multiple stress cycles for a single truck passage, but a few large cycles may be caused by the combination of individual truck crossings. The modular joints on the 3rd Lake Washington bridge have relatively long centerbeam spans. The fatigue problem is most serious in the edge centerbeams because of the larger stress *range* produced by the alternating long and short spans. The analyses showed that a much larger

stress range is possible between different trucks because the trucks do not travel over the same path across the joint. This variability may double the stress range over that computed for a single wheel load.

The elastomeric springs and bearings are an important element in joint behavior. However, they have frequently been reported as being loose in the joints. The precompression or looseness of the bearings will affect local bending stress in the critical region surrounding the stirrup and may also lengthen periods of critical modes of centerbeam vibration. However, precompression is not thought to be a predominant contributor to the fatigue problems noted in the joints.

The Tschemmernegg design load spectrum and S-N curves are based on field measurements, analysis, and fatigue tests of modular joints in Europe. Fatigue design criteria for modular joints must consider the unique features and dynamic response of each joint system. The fatigue test must be appropriate for the loads the joint experiences, or it will lead to improper S-N curves and failure modes. The fatigue test on the as-built tubular centerbeam may not indicate the fatigue behavior of this joint because the fatigue test does not include the flexibility of the joint with respect to horizontal loads.

There are clear variations between theoretical calculations and the prior design and research studies. Most of these differences appear to be related to individual differences in the design and construction of the modular joint system. The manufacture of expansion joints is a highly entrepreneurial business, and each system has unique features. This research was largely started as a means of examining and investigating these differences.

PROCEDURES

EXPERIMENTAL REQUIREMENTS

A number of difficulties are encountered in performing field measurements on modular joint systems. First, the vehicle loading of a modular joint is of very short duration, and individual components of the joint may be loaded for only a few hundredths or thousandths of a second. As a result, very rapid or continuous data sampling is required to obtain useful information regarding the dynamic response of the joint. Second, huge volumes of data can be accumulated in a very short period, and therefore a filtering technique is needed to assure that only the most useful data are recorded and stored. Third, there is a high degree of uncertainty regarding trucks that ordinarily cross the joint. The dynamic response of the joint due to the truck crossing the joint and the effect of the dynamic response on the stress range for the fatigue critical locations of the joint are important considerations. However, these depend upon many factors that are not known when the truck crosses the joint. These factors include vehicle speed, wheel load, wheel size and spacing, axle span, vehicle position in the driving lane, driving conditions (constant speed, braking, or accelerating), and the spring characteristics of the suspension systems of the vehicle. None of these factors are known for a given vehicle crossing the joint. As a result, the instrumentation and field measurement plan must be sufficiently robust to encompass a wide range of conditions, and it must provide a wide range of information.

INSTRUMENTATION

The instrumentation for this research had to be selected with the view of addressing these issues. First, the joint selected for this experimental study was the 1200 mm joint at the east end of the eastbound lanes of the bridge. The joint at the east end was selected because it was more readily accessible, requiring less climbing. Because of the larger

movement capability, there was adequate space for installation of gages and instruments. The eastbound direction was chosen because a somewhat larger number of fatigue cracks were noted in this direction. However, the selection of this direction caused some additional problems and concerns. First, these lanes were converted to reversible lanes after September 10, 1993, because of the reopening of the Lacey B. Murrow Floating Bridge. This presented additional possibilities for the accumulation of data on the bridge, but it also placed a severe time constraint on the measurements. Normal truck traffic was not permitted on the reversible lanes, and so all load spectrum measurements had to be completed by September 10, 1993.

Two types of measurements were performed. Most measurements were strain gage measurements. The strain gages were assembled into a 4-gage (full Wheatstone Bridge) assembly. The wiring and the placement of the gages varied depending upon the desired measurement. Most gage assemblies were installed to directly measure curvature of a centerbeam under vertical or horizontal bending moments. The curvature was measured directly and depended upon the gage factors of the strain gages; the bending moments could be directly determined at the measured locations by multiplying curvature times the elastic stiffness (EI) of the centerbeam. All instruments were installed to measure truck traffic in the right hand (outside) lane of the eastbound traffic. The gages were centered about centerbeam 13 (CB13) of the joint. This centerbeam was selected because it is near the outside edge of the joint. Prior analysis (Roeder, 1993; Roeder, Hildahl, Van Lund, 1994) had indicated that these outside centerbeams experienced larger stress ranges because of the greater variability in the span length of these outside beams. Further, most of the past fatigue cracking has been noted in the centerbeams near the outside edges of the joint. The gages were installed at locations where significant bending moment was expected, so reasonable accuracy and sensitivity of the measurements could be achieved. At the same time, they were placed at positions that provided redundancy of the measurements.

Figure 7 shows the six basic locations used on CB13 for this test. These were the locations used for nearly all measurements. Channels 1 through 4 measured curvature (and as a result bending moment) at four locations near the right hand lane. These bending moments could be used to estimate the location of the vehicle in the driving lane and the dynamic wheel load of the vehicle. The determination of the location was made by comparing the moments measured at the four locations to the bending moment diagram expected for the joint. Figure 8 shows a typical bending moment diagram and influence lines computed for CB13 with a given wheel geometry. The full range of these bending moment diagrams can be translated into influence lines such as that depicted in Figure 9. Note that the development of the influence line assumes a given wheel spacing and geometry (tire width, dual or single wheels, wheel spacing, and axle length), and so there is still uncertainty in the measurements. However, the influence line can be generated for some average properties, and this information can be used to generate a wheel load spectrum for average truck geometry.

Additional field measurements were also conducted, but on limited or specific tests. One major objective of the measurements was the determination of dynamic loads on the joint components. The stirrups of the joint would be under tension because of the precompression of the elastomeric springs in the joint. As the joint was loaded, the stirrup load would theoretically change, and so a few strain gage sets were installed to measure the change in force in the stirrup. Note that the cross sectional area of the stirrup was relatively large, while the magnitude of the forces would be fairly small. Thus, very small strains were expected here. Full bridge connections for measurement of axial load were employed. However, because of the very small magnitude of the strain being measured, these measurements did not provide much useful data and will not be discussed further in this report.

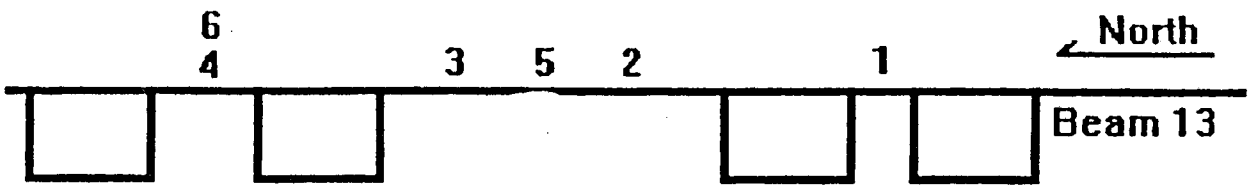

Figure 7. Basic Strain Gage Placement on CB 13 for Bending Moment Determination

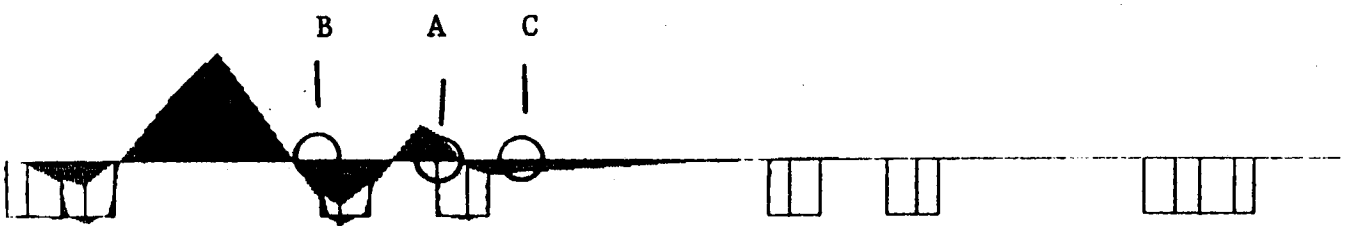

Figure 8. Typical Vertical Bending Moment Diagram for CB 13

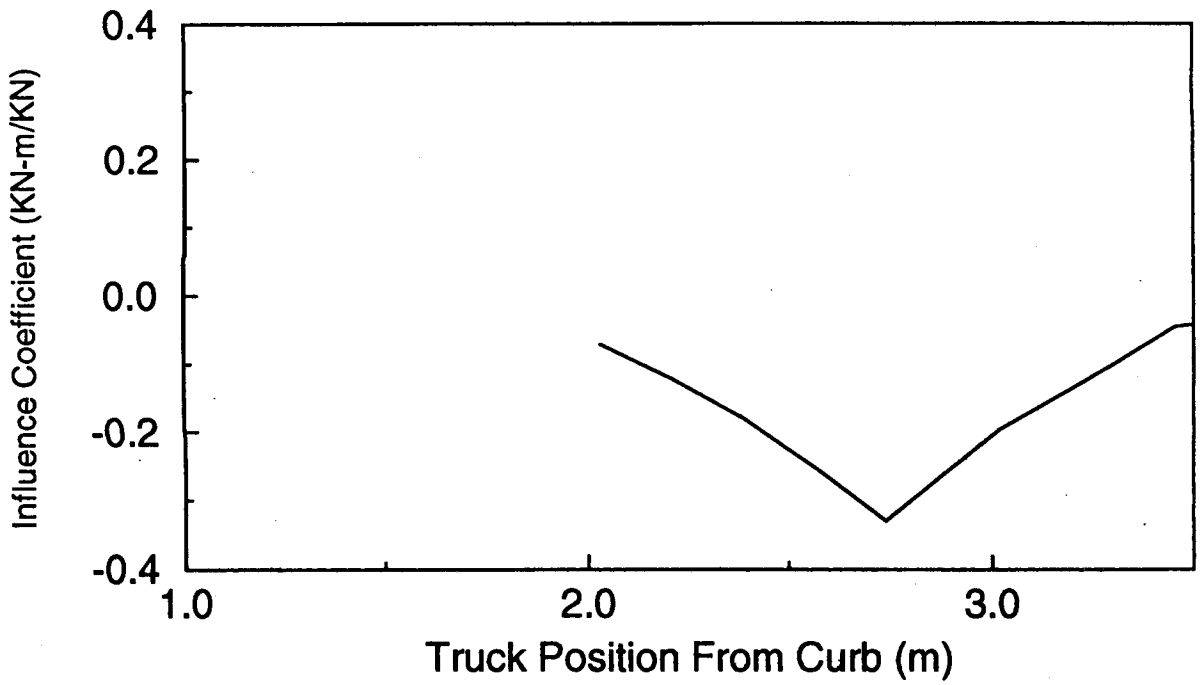

Figure 9. Typical Influence Line Postulated for CB 13

Strain gage measurements of vertical curvature and bending moment in adjacent centerbeams (CB12 and CB14) were also used in a few controlled tests. The full bridge strain gages were similar to those used on CB13, and comparison of the bending moments obtained in adjacent spans provided information about load sharing between centerbeams. Tschemmernegg (Tschemmernegg, 1988; Pattis and Tschemmernegg, 1992; Brown, 1991) has proposed a series of rules for distributing load between centerbeams, and this study provides data to check Tschemmernegg's procedure. Finally, horizontal deflections of the centerbeam were measured on CB13. One measurement was made near midspan near Channel 5 and the other near Channel 4 in Figure 7. These measurements were sometimes used instead of basic Channels 1 and 4. Channels 1 and 4 were selected because the moments and curvatures measured at these locations were generally less interesting and less useful unless the truck crossed the joint with an unusual path. The horizontal deflection

measurements were very important because the Tschemmernegg fatigue design procedure is based on the assumption that the support points are fixed against both vertical and horizontal movement; these measurements provided a check of this hypothesis.

The basic data were recorded with three HP5813A wave form recorders. Each wave form recorder handled two channels of data. The wave form recorders were capable of recording up to 4000000 samples per second of data per channel, but they were sampling at the rate of 2000 samples per second for these tests, a rate more than ample to measure the joint response. The three recorders were coupled together and were self triggering. That is, the recorders continually sampled data, but they only recorded data when a big enough measurement was noted. At this time a short burst (2 to 3 seconds) of data was recorded. The data recorders could record a number of trucks until their internal memory was full. The data were then transferred to an HP9816 computer and were stored in a compact binary format in an IEM 5300 (330 megabyte) disk drive. This operation was automatic, and no intervention by the researchers was required. The system could operate day and night and detect all trucks in the right hand lane. The wave form recorders measured voltage only. The normal voltage was the unbalanced voltage across the Wheatstone Bridge. This was a very small voltage difference, and so it was amplified with Micromeasurements 2100 System signal conditioners to improve the accuracy of resolution of the data. Figure 10 is a photograph of the basic field experimental equipment and setup. The disk drive was portable (approx. 14 lbs.), and it was carried into the University of Washington campus when it was full. The disk drive was transferred again by an HPUX 700-340 computer, and the data could be analyzed by the normal research computer facilities.

Only six channels of data were recorded by the recorders. This was adequate for most of the measurements, but a few additional channels were used on a few control tests. The additional data were recorded by an HP3852A data acquisition system. Up to eight

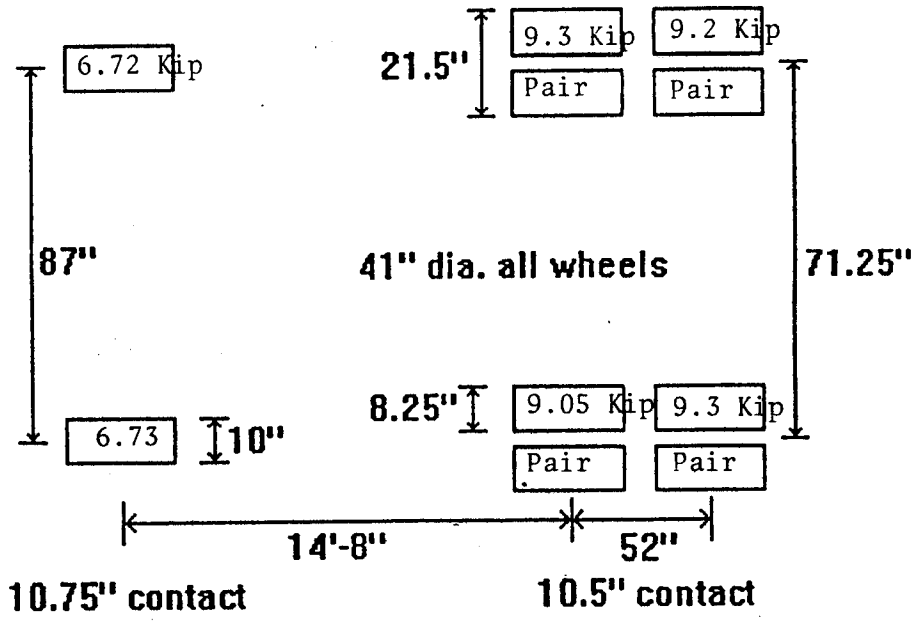

Figure 11. Static Wheel Loads and Geometer of Truck used for Controlled Load Testing

establish basic elements of joint behavior such as the effect of truck position, truck braking or acceleration, direction of travel, and distribution of load between centerbeams. The results were used in interpreting the second type of test results.

The second type of test consisted of measurements of uncontrolled truck and bus traffic in the right lane and its effect on the joint. The six basic channels illustrated in Figure 7, monitored by the HP5813A wave form recorders, were used for the uncontrolled traffic measurements. The recorders were set to record data when a sufficient signal was received by either of Channels 1, 2, or 3. The signal was set such that a truck in the middle lane would not trigger the device, nor would a heavy car or light truck in the right lane. This required some manual observations of truck traffic and the truck size necessary to trigger the instruments. Pick-up trucks, vans, and similar vehicles were not permitted to trigger the data acquisition. Data were recorded continuously in blocks of 10 trucks. The

data storage and record naming procedure allowed determination of the approximate time of the truck group during the data analysis. Large variations in truck traffic volume were noted. Weekend and holiday traffic volumes were very light, and late night traffic volumes were clearly lighter than those of day traffic. Data were accumulated over a two and a half-week period ending September 10, 1993. A few trucks were missed during the short period required to transfer the block of data from the wave form recorder to the computer, but the percentage was small. Electrical power limits also resulted in some lost data during short periods. Further, many lighter trucks were missed because they were not heavy enough to trigger the instruments. However, a large number of trucks were measured. To illustrate the number of trucks recorded, during the 24-hour period of Wednesday, September 1, 1993, 990 heavy vehicles were measured in the right hand lane of the eastbound I-90. This is not inconsistent with a truck traffic count of November 13, 1990, when a total of 6720 axles were counted in all of the westbound lanes during a 12-hour period. The 990 trucks would result in nearly 5000 axles in a single lane for a 24-hour period.

The uncontrolled truck traffic measurements were used to establish a fatigue load spectrum for vertical and horizontal wheel loads on the joint. These loads were not static wheel loads but were dynamic loads that included the effect of impact and dynamic amplification or attenuation. The six basic channels (four for vertical bending and two for horizontal) directly measured the bending curvature, and the curvature was translated into bending stress, bending strain, and bending moment as desired. The variation and distribution of stress are quite interesting, as they affect fatigue behavior. However, the stress and bending moment at the strain gage locations depended upon the placement of the wheels on the centerbeam, and this placement was not known for the uncontrolled traffic measurements. The first four channels of measurements allow estimation of the vertical plane bending moment at four locations on the centerbeam under one lane of traffic. Theoretically, these four moments should have been enough to estimate both the magnitude

of the dynamic wheel load for vertical loading on the centerbeam and position of the wheel on the joint through influence lines developed for each gage location. Note that the influence lines depended upon dynamic effects as well as static loading and truck size. More measurements were made than were actually needed to determine load and position. This provided redundancy, which could be used to verify and improve the accuracy of the estimates. The position of the vehicle wheels, combined with the two horizontal plane bending moments, allowed estimation of the horizontal wheel load on the centerbeam. The combination of these loads for all of the trucks measured on the joint allowed development of a fatigue wheel load spectrum.

DATA CORRECTION AND ANALYSIS

The controlled field measurements required only limited data interpretation and analysis. The digital wave form recorders stored the measured voltage as a binary file in a least count integer format. This resulted in a minimal storage space requirement, even though a very large quantity of data was stored. Once the data were recovered from the field disk drive, the digital data were first converted to a normal voltage measurement, and this voltage was multiplied by a calibration factor to determine the curvature, deflection, or bending moment as appropriate. The conversion from integer to normal voltage format was performed with a simple equation using scaling data stored at the front of the data file by the digital recorder. Once the data had been converted to voltages, bending moments, and deflections, they were restored in ASCII format where they could then be plotted or used in normal data analysis. This ASCII format required a much larger data storage space, but it could readily be passed between computers and be read and interpreted by nearly any device. Approximately 2 gigabytes of data were stored in this format from the field tests. The controlled test results were a small portion of these data, and the controlled test data could readily be analyzed and evaluated by physically examining and plotting each file. Interesting observations could be noted and conclusions could be drawn where appropriate.

The uncontrolled load spectrum measurements required all of the analysis noted above, but considerable additional analysis was also required. First, the huge quantity of the data prevented the researchers from manually evaluating and analyzing each data file. Thus, automated procedures for data analysis had to be developed. Second, the data were automatically recorded and stored. Electronic instrumentation tends to drift or change with time. These changes can partly be attributed to changes in electrical resistance caused by time and temperature, outside electrical interference, or by temporary malfunctions of an individual circuit. Temporary aberrations may also have been caused by bridge traffic. The uncontrolled truck data were stored in blocks of 10 trucks. The time required to accumulate 10 trucks of data could be as small as 5 or 10 minutes during busy portions of the day or as much as an hour during weekends, holidays, or early morning hours. Once a block of 10 trucks had been stored, the computer checked the data acquisition equipment, re-initialized itself, and started to record more data. The binary data files containing these 10 trucks were identified by the notation "sdxxTyyyyyy", where xx was the day number (1,2, 3, and etc) of the test and yyyyyy was the time of day measured in seconds (0 up to 86400) after midnight. This identifier allowed the researchers to tell the time that the data were acquired and the time required to complete the 10 truck measurements. However, because of the long periods required to complete 10 trucks at some times, inadvertent drift was included in the data.

The first task in the analysis of the data was to scan the data to determine whether any offsets or malfunctions existed in the individual data channels. Figure 12 illustrates a typical offset data recording. It shows that the initial and final voltage readings were not returning to zero, most probably because of circuit heating. The offset seemed particularly prevalent late, at times when traffic was very light, because the equipment then had a long time to drift without benefiting from the periodic correction provided by the controlling computer system. These offsets were corrected very easily by removing the offset from all

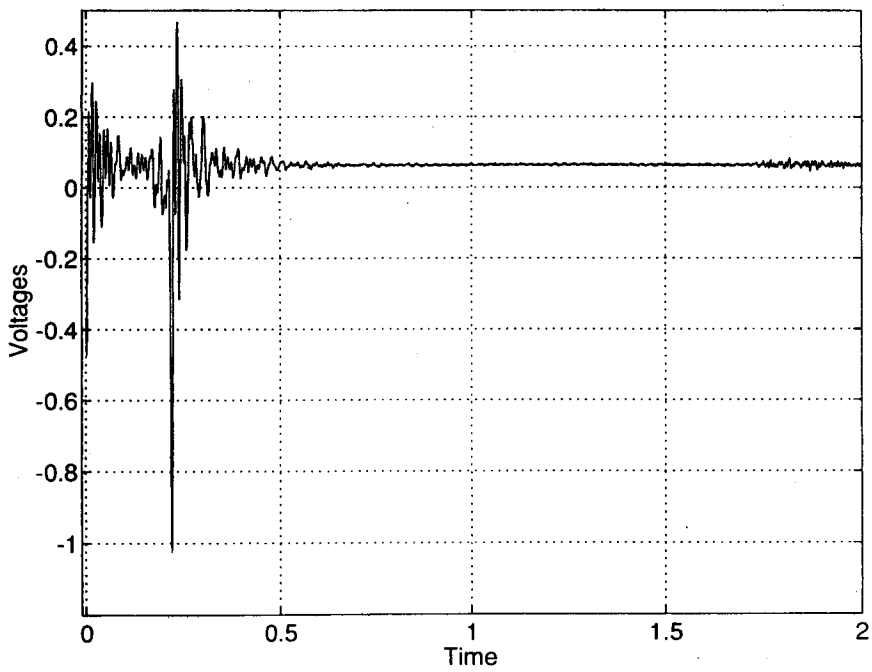

Figure 12. Typical Offset Data Recording

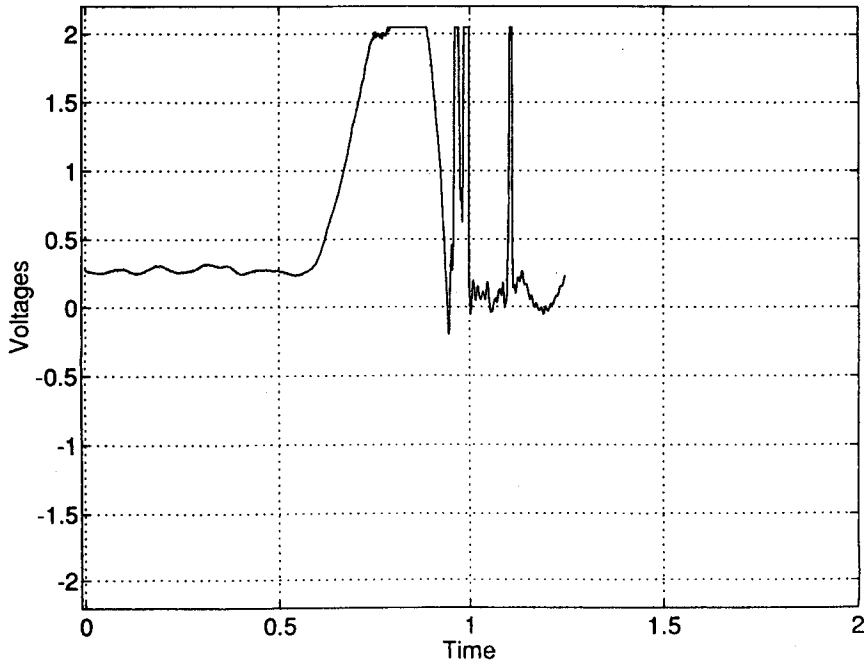

Figure 13. Typical Out-of-Range Data Channel

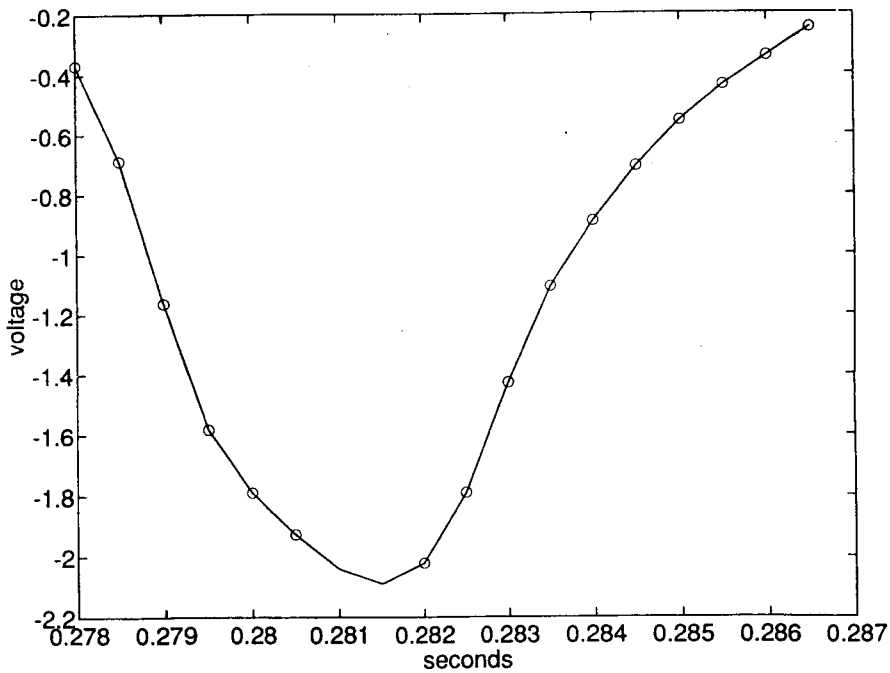

Figure 14. Typical Spline Correction for Out-of-Range Voltage Data

voltage measurements on that file. Unfortunately, the offset caused other problems.

On occasion some vehicles went out of the voltage measurement range, as illustrated in Figure 13, because of the initial offset. These out-of-range vehicles were also identified, and the data were corrected. A few channels went out of range because the trucks were very large. Some out-of-range problems were caused by a combination of large trucks and a voltage offset that evolved during the test. However, the number of out-of-range channels was not large. A method for establishing the out-of-range peaks was established for these cases, and as a result these lost data were recovered. Figure 14 provides an example of the data recovery for the overrun illustrated in Figure 13. The recovery method used a variation of the spline function, combined with the existing end conditions before and after truncation. The data were recovered for a very small number of

trucks, and the recovery method was quite accurate. The accuracy was evaluated by arbitrarily truncating some curves with complete data and using the procedure to regenerate the truncated data for comparison. The generation method appeared to consistently estimate the peak moment within 2 or 3 percent, and the estimate was consistently smaller than the true peak. As a result, these recovered data would be an important contribution to the load spectrum but would not skew or distort the test results.

Figure 15 illustrates a data file that appeared to be influenced by some unknown, outside electrical source or had another form of temporary malfunction. Channels 1 and 4 appeared to be particularly susceptible to this problem. However, these temporary dysfunctions occurred on only a few trucks and normally occurred on one channel at a time. These dysfunctional data were simply neglected, as the six channels for the single centerbeam provided a basic redundancy in the measurements, and it did not appear to be possible or practical to regenerate this information.

Once the data had been scanned and checked for general accuracy, they were carefully analyzed to determine wheel loads and rebound cycles. A computer program was written to perform this operation. Figure 16 illustrates the wheel loads determined from voltage measurements of a typical truck crossing. The wheel location program cycled through the incremental time history of each data file until a peak wheel load was located on one of the data files. Once this peak had been located, the corresponding peaks and rebound peaks were read for all six data files. Rebound and free vibration peaks after completion of the wheel crossing were noted for each channel until the amplitude was less than approximately 10 percent of the peak. The time and amplitude of each peak for each channel were recorded. Each wheel record contained many peaks, and each truck record contained several wheels. In this manner, all the information on nearly 20,000 trucks was condensed into a series of summary files, which were used to estimate the wheel load spectrum.

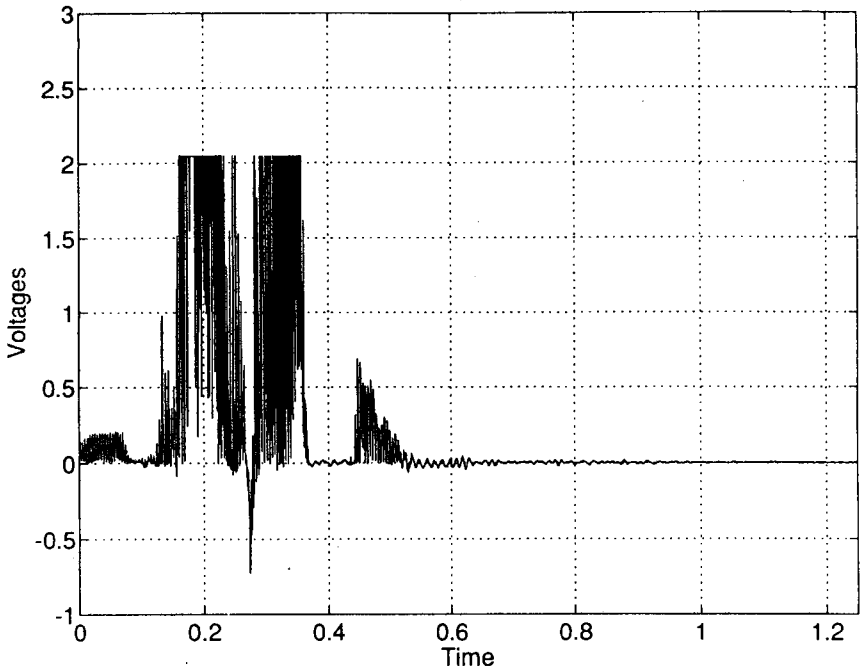

Figure 15. Data Influence by Outside Electrical Noise

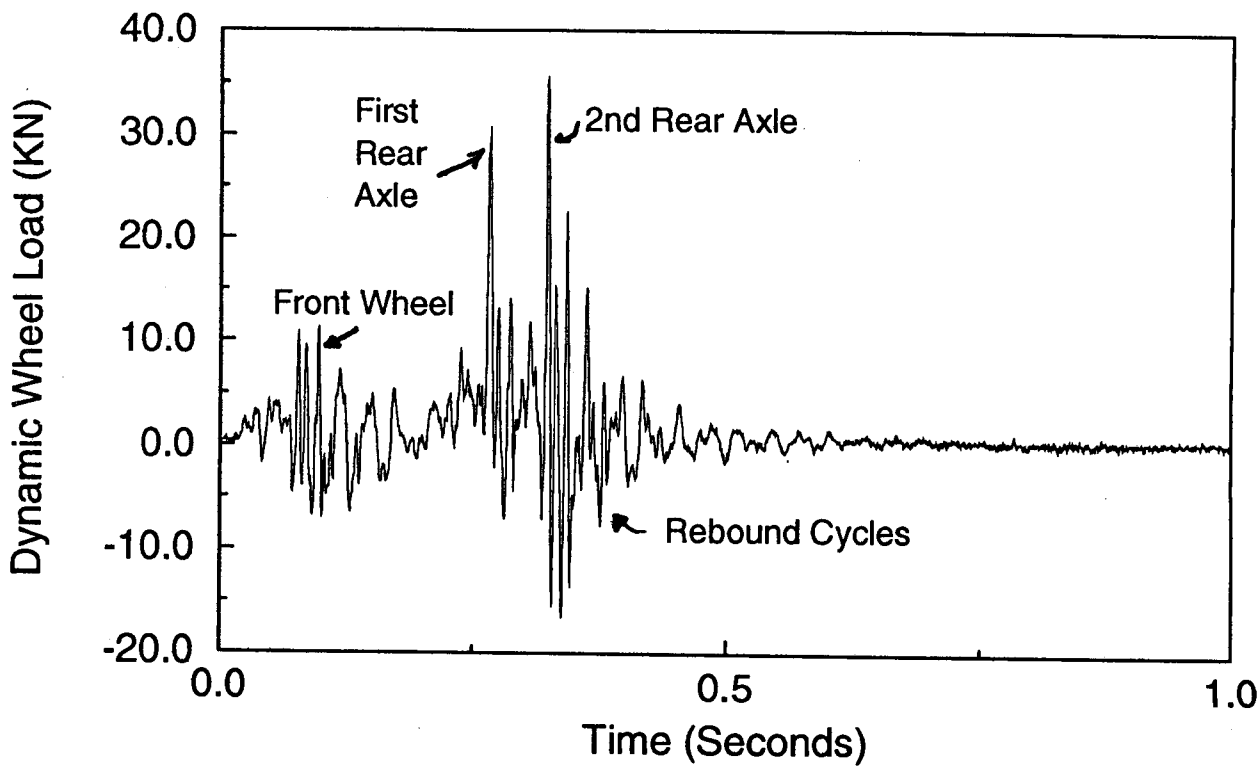

Figure 16. Typical Wheel Load and Rebound Cycles of a Truck Crossing

The summary files of times and voltages were then converted to bending moments and times for each wheel of each truck. The bending moments could then be translated into estimated wheel loads with the aid of influence lines and moment diagrams. This second operation is discussed in greater detail in the next chapter.

DISCUSSION

RESULTS OF CONTROLLED TESTS

Two series of controlled tests were performed (Hildahl, 1993). During August 17 through 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 17 is a photo of the test truck for the controlled tests. Figure 11 shows the static wheel loads and dimensions of the test truck. The truck passed over the joint at known speeds and locations 24 times during the two-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 sometimes traveled at a known constant speed and at other times at a known speed with braking or acceleration.

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 provided many more options in the speed and placement of the vehicle on the joint. Forty-two load passes were made with the same truck used in the earlier tests and a nearly identical loading. Nearly all of the truck passes were made at various points within the outside (southern-most) lane, so that the greatest amount of useful information regarding truck location could be obtained. Most of the tests were performed with eastbound truck traffic, but a few passes were performed with a westbound truck. These tests may be useful in interpreting future reversible lane measurements. 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 would be used to establish basic elements of joint behavior, such as the effect of truck position, truck braking or acceleration, and the distribution of load between centerbeams. The results would also be used to interpret the second type of test results.

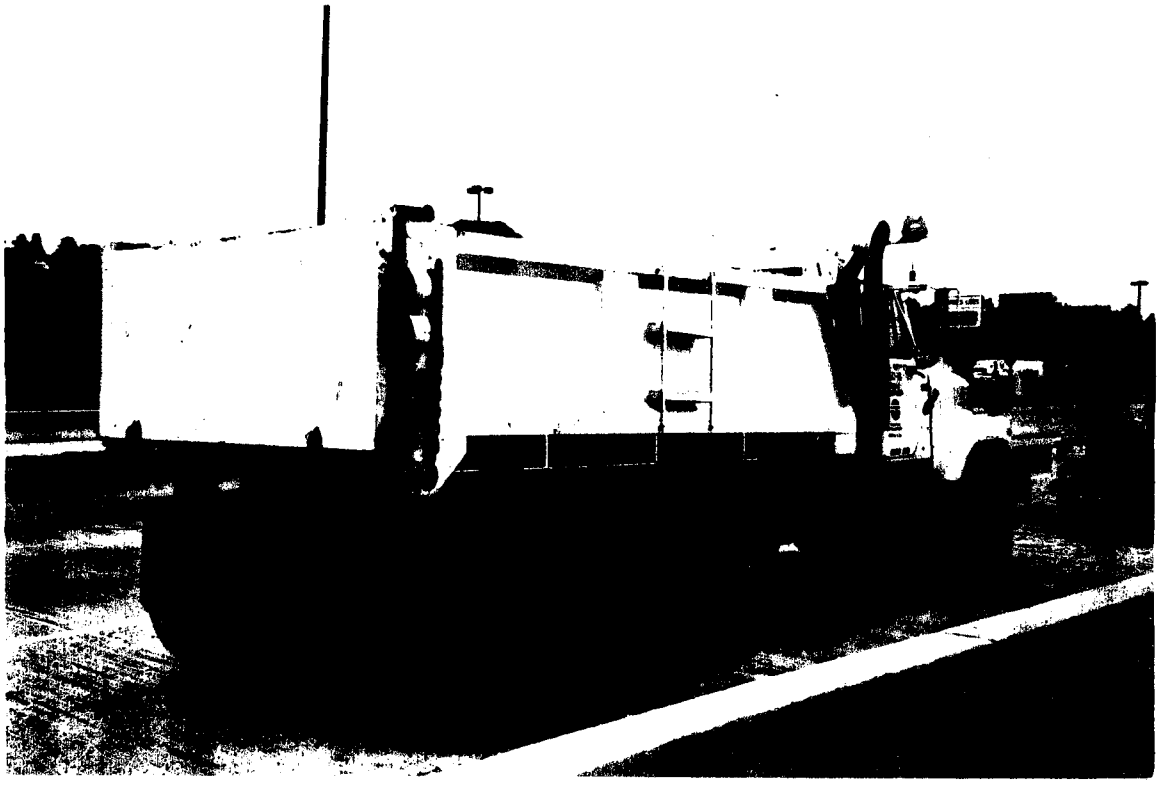

Figure 17. Photograph of Test Truck

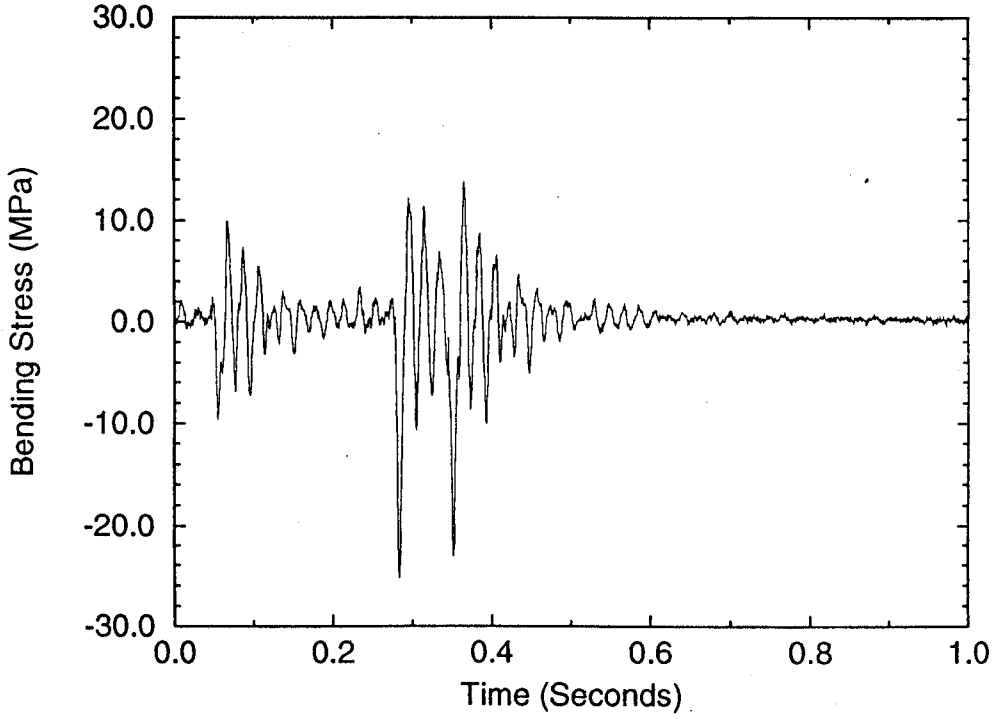

Figure 18. Measured Stress Range in the Modular Joint with Truck Crossing

Given the voltage measurements recorded from these tests, the bending moments as a function of time could be directly determined, and bending stresses could be determined from the bending moments. Figure 18 shows the stress at a location typical of those with fatigue cracking while a truck crossed the joint. It shows that each wheel caused a sharp stress increase, and a rebound cycle is noted on the graph after the wheel left the centerbeam. The rebound depended upon the speed of the vehicle and the dynamic characteristics of the joint. A series of free vibrations occur on the graph after the rebound cycle. This free vibration could be used to determine critical information about the dynamic behavior of the joint, as illustrated in Figure 19. First, the period of vibration was inferred from the time observed between peaks of free vibration. This was not an exact determination, as the vibration depended upon the initial conditions and the mode excited by the loading. There were a large number of modes of vibration to be excited (Roeder, 1993; Roeder, Hildahl, Van Lund,1994), but they tended to have closely spaced periods. Some of these dynamic characteristics are summarized in Table 1. Periods of vibration in the range of 0.012 to 0.025 seconds were noted for vertical loading and periods of 0.03 to 0.05 seconds were typically measured for horizontal loading. Periods as long as 0.12 seconds were noted when the truck crossed the joint with severe braking. The longer measured periods appeared to be associated with larger amplitude motion where the period may have been increased by larger deformation of the elastomeric spring or by sliding movement in the joint. The shorter periods were associated with smaller amplitude vibration where greater stiffness of the supports could be expected. These periods agreed well with those computed in earlier dynamic analysis of the subject joint. The damping was estimated from the logarithmic decrement of the decay of the free vibration. This damping varied from case to case but was estimated to be approximately 6 to 13 percent of critical. Again, the larger damping was often associated with larger amplitude motion. Even larger damping was noted with braking or acceleration of vehicles because of internal

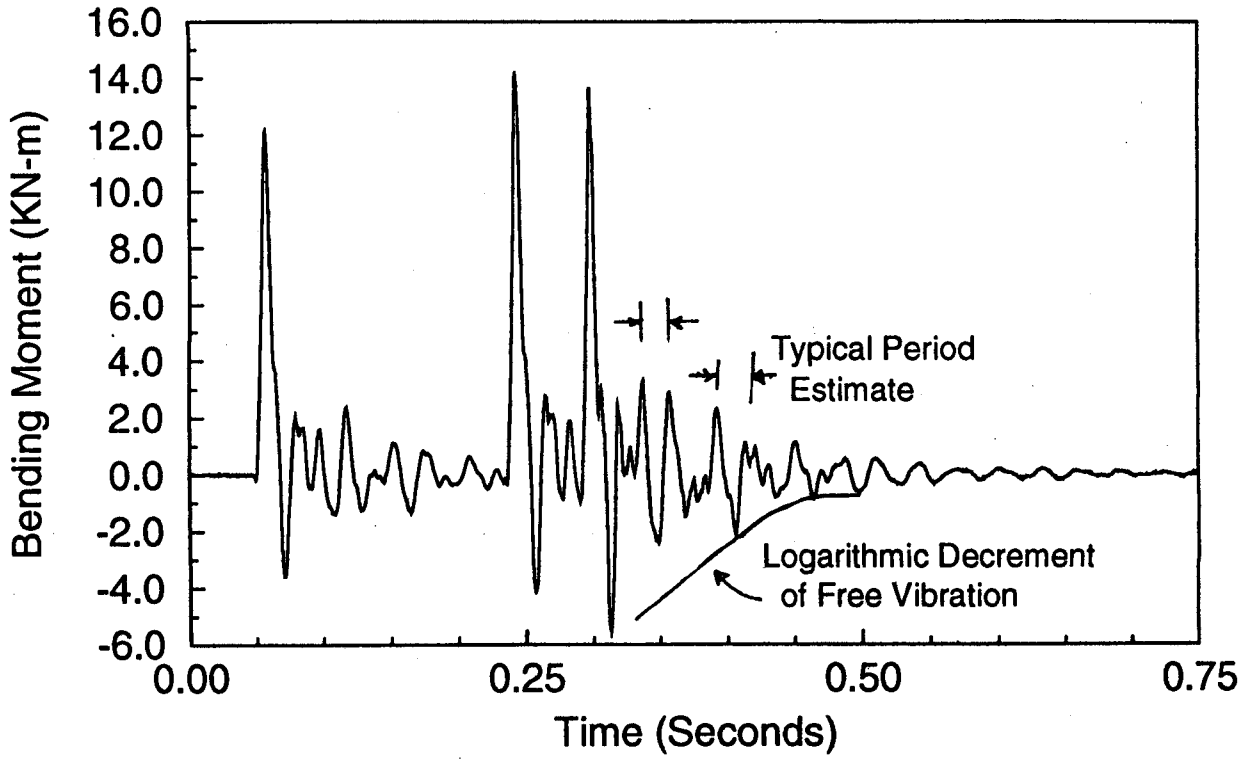

Figure 19. Determination of Dynamic Period and Damping from Joint Vibration

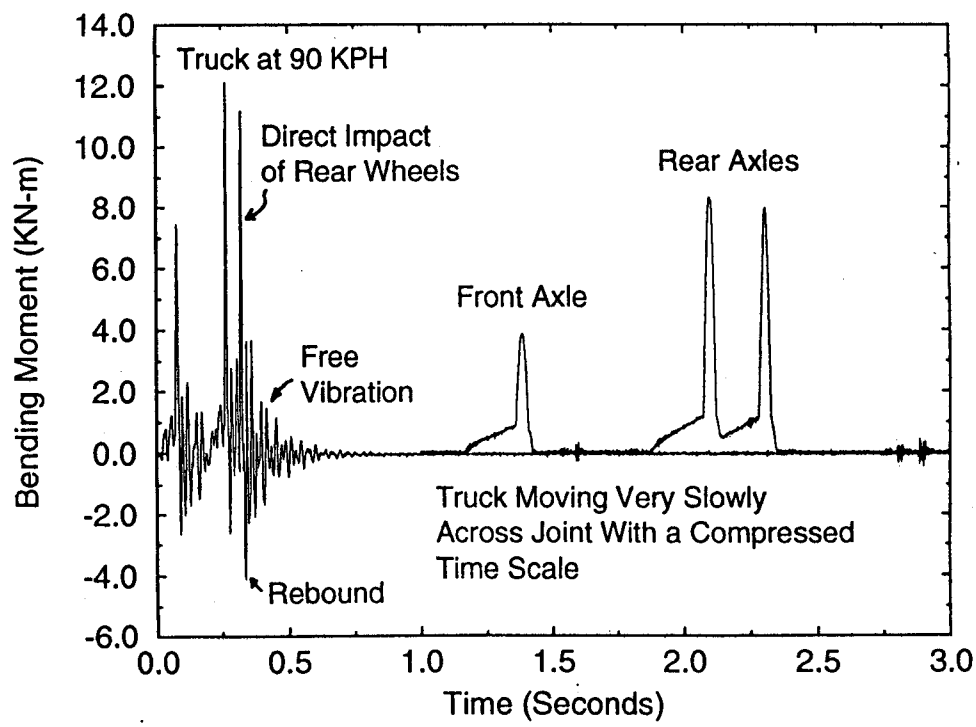

Figure 20. Measured Bending Moment in Centerbeam Due to Vertical Wheel Loads at 90 kph and Static Conditions

Table 1. Typical 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.
Vertical Damping	6 to 13% of Critical Under Normal Vibration	No Estimate	Approx. 7.1 %

movements and friction of the joint components. Table 1 also compares the measured data to results obtained by Tschemmernegg on field measurements from the Werratal Bridge. The comparison to Tschemmernegg data showed good correlation between the measured damping values. Comparison suggested that similar but somewhat shorter periods for vertical modes of vibration occurred on the 3rd Lake Washington bridge. Horizontal modes of vibration were much more variable in the theoretical calculations and in these tests than reported by Tschemmernegg. Very long periods of vibration were computed and measured when the vehicle was braking or accelerating over the joint. Very little mass participates in the modes of vibration associated with these long periods. As a result, these modes are excited only by severe truck loadings, which cause rigid body movements of the centerbeam.

Figure 20 shows the typical measured bending moments created by the controlled test truck passing over the joint with nearly the same path both very slowly and at 90 kph (55 mph). The trucks maintained constant speed as they crossed the joint and neither braked nor accelerated. The axle loads were approximately 80 kn (9 tons) for each of the two rear axles and 67 kn (7 tons) for the front axle. The dynamic load experienced by the joint was proportional to the maximum bending moment. Comparison of the two truck crossings showed that the vertical loads for the high speed vehicle were amplified 30 to 40 percent over the static loading. This measured amplification was typical of other values obtained at similar vehicle speeds. Figure 20 shows that a peak centerbeam bending moment was achieved as the wheel crossed directly over the centerbeam, and a dynamic rebound occurred as the wheel left the centerbeam. Tschemmernegg's fatigue design loads have a dynamic rebound of 27.1 kn (6.1 kips), which is approximately 40 percent to 45 percent of the maximum direct static wheel load and approximately 30 percent of the vertical load, including impact on the joint. The rebounds shown in Figure 20, which are fairly typical of those observed throughout the test for these driving conditions, were in the order of 30 percent to 50 percent of the direct impact loading with the truck traveling at 90

kph (55 mph). However, there was no rebound with the static loading, and this suggests that the rebound effect may be smaller with slower moving vehicles.

After the wheel left the centerbeam, the beam vibrated in 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 20 suggests that the period of the centerbeam vibration was approximately 0.015 seconds. Prior computer analysis (Roeder, 1993; and Roeder, Hildahl, Van Lund, 1994) showed that many, closely spaced modes of vibration contributed to the dynamic response of these joints in both the horizontal and vertical planes. The computed periods ranged from 0.05 second to 0.005, second with 0.015 second as an approximate average value. Thus, it appears that the measured period for vertical vibration of the centerbeam was consistent with that predicted in the theoretical calculations. Further, the duration of a ramp loading on an individual centerbeam with the vehicle speed noted in Figure 20 was approximately 0.0125 seconds. The ratio of this duration to the period of vibration was approximately 0.85, and the theoretical dynamic amplification predicted by Figure 6 was approximately 50 percent. These combined observations suggest that the correlation was quite good between earlier (Roeder, 1993; and Roeder, Hildahl, Van Lund, 1994) theoretical predictions and experimental predictions when vehicles were moving at speeds near 90 kph (55 mph).

Figure 21 shows the horizontal plane bending moments measured with the truck at 90 kph (55 mph) and with essentially a static loading. The vehicle crossed the joint with essentially no braking or acceleration. However, note that the joint was on a slight 3 percent to 4 percent grade, and this grade necessitated some minimal acceleration to maintain driving speed. In addition, the inclination resulted in a small vector component of the gravity load in the "horizontal" direction. Note also that the bending moments were proportional to the dynamic force felt by the centerbeam. Earlier dynamic analysis (Roeder, 1993; and Roeder, Hildahl, Van Lund, 1994) suggested that this joint system was

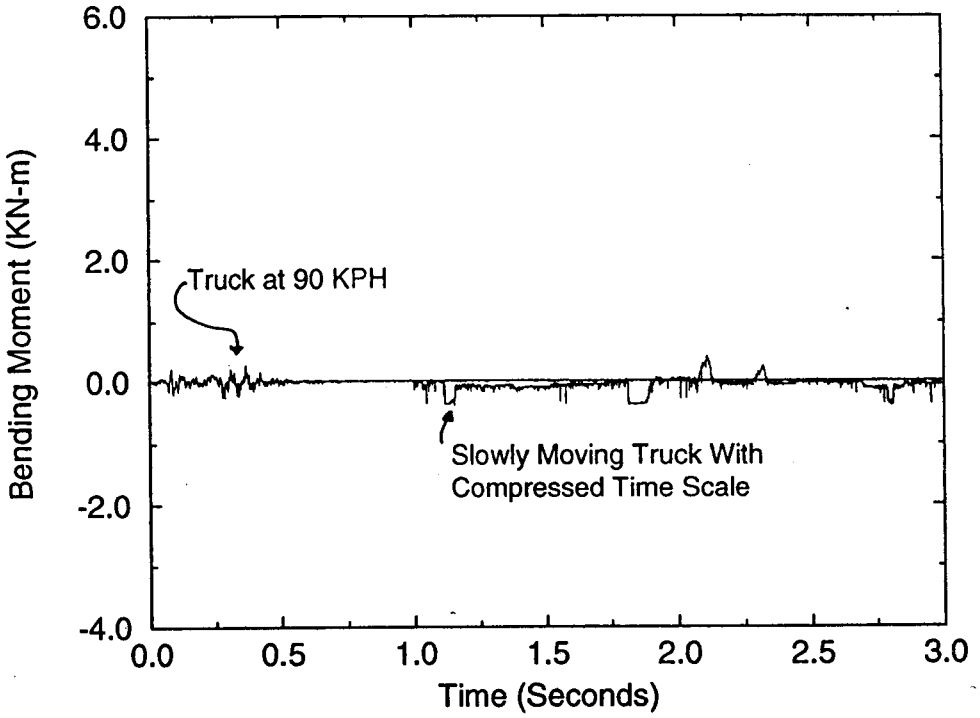

Figure 21. Measured Bending Moment in Centerbeam Due to Horizontal Wheel Loads at 90 kph and Static Conditions

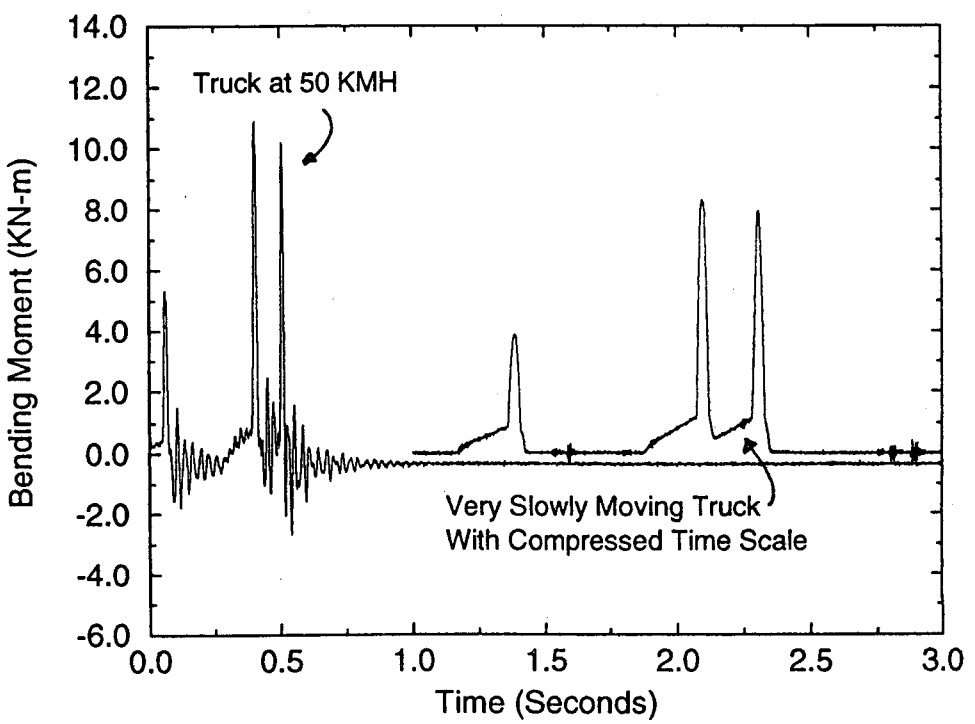

Figure 22. Measured Bending Moment in Centerbeam Due to Vertical Wheel Loads at 50 kph and Static Conditions

very flexible in horizontal loading, and as a result researchers postulated that the centerbeam could not experience a large horizontal load. On the other hand, the Tschemmernegg fatigue evaluation procedure 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 must be modeled as a rigid connection for the horizontal loading. Comparison of the moments in Figure 21 to those obtained in Figure 20 suggest that the dynamic force acting in the horizontal direction would have to be well under 10 percent of the vertical load if this rigid support assumption were applied.

Figure 22 shows a similar, typical comparison to Figure 20 with the truck driving at a much slower speed (approximately 50 kph or 30 mph). The dynamic amplification was in the range of 25 percent to 35 percent of the static load. The duration of loading was longer at this reduced speed, and the ratio of the duration to the period of vibration for the centerbeam was proportionally larger (1.55 as opposed to 0.85). Thus, the theoretical amplification from Figure 6 would be approximately 25 percent, because the load duration in Figure 22 falls on the right side of the hump of the curve. These comparisons were generally consistent with the earlier theoretical predictions. The dynamic rebound was quite large at the higher speed, but it was smaller at lower speeds, as illustrated by comparison of Figures 20 and 22. The rebound was obviously zero under static loading. The rebound was about 40 percent to 50 percent of the vertical load at 90 kph (55 mph) and was about half this amount at 50 kph (30 mph).

Figure 23 shows the horizontal bending moments due to the same truck as shown in Figure 22 crossing the modular joint. The truck was crossing the joint at a position similar to that shown Figures 20 and 21. Figure 23 shows that the horizontal force at 50 kph (30 mph) was somewhat larger than that noted for the 90 kph (55 mph) vehicle. However, in both cases the bending moment and horizontal force were much smaller than the vertical load. The majority of the participating mass in the horizontal modes of

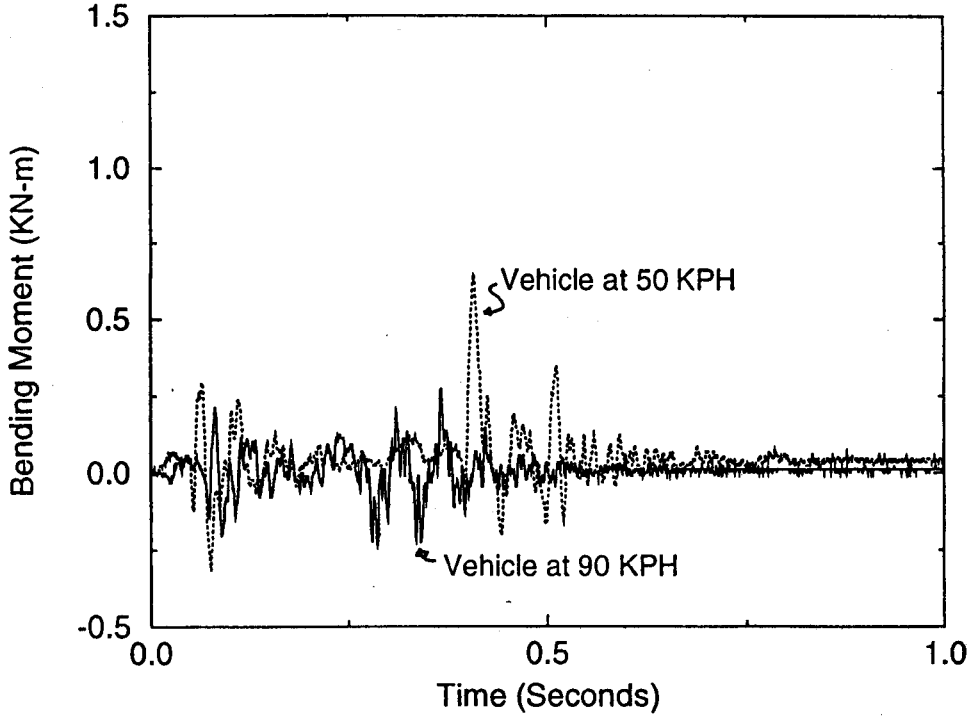

Figure 23. Measured Bending Moment in Centerbeam Due to Horizontal Wheel Loads at 50 and 90 kph

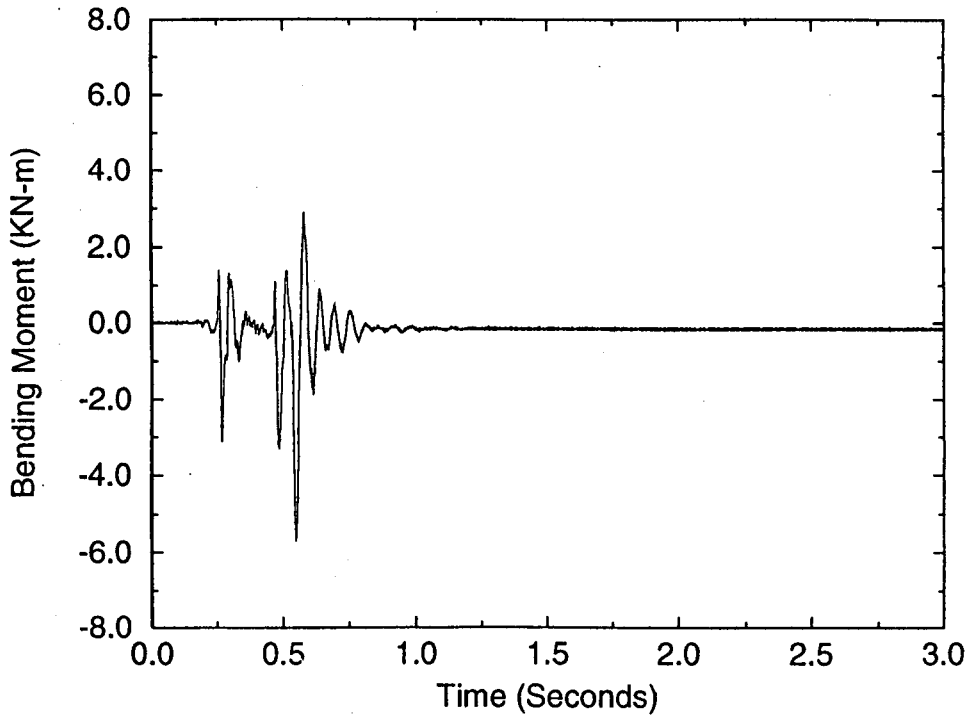

Figure 24. Measured Bending Moment in Centerbeam Due to Horizontal Wheel Loads at 90 kph With Moderate Braking

vibration were resident in modes with periods of between 0.16 and 0.035 second. Therefore, the ratio of the duration of load to the period varied between a high of approximately 0.6 at 50 kph (30 mph) and 0.0 at 90 kph (55 mph). Figure 6 shows that the dynamic amplification approaches a maximum of 1.5 at the slower speed and is much smaller at 90 kph (55 mph). Figure 23 is consistent with this observation, since the dynamic moment was approximately twice as large for the slower speed as for the higher speed, but in both cases the horizontal load was much smaller than that suggested by the Tschemmernegg design method.

The horizontal loads were much smaller than those suggested by the Tschemmernegg fatigue design procedure under normal driving conditions. If a vehicle was braking or accelerating as it crossed the modular joint, the horizontal forces were much larger. Figure 24 shows the horizontal load bending moments with moderate braking when the truck was moving at approximately 90 kph, and Figure 25 shows the moments with emergency braking at a similar speed. Comparison of the figures shows that vehicle braking caused much larger horizontal dynamic loads than those suggested by Tschemmernegg. These bending moments were 10 to 20 times larger than those noted with normal traffic.

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. Figure 26 shows the horizontal movements measured if a truck crossed the joint with no braking or acceleration. The figure shows no significant horizontal movement and no permanent set in the displacement. In contrast, Figure 27 shows typical centerbeam movement if the truck was braking to an emergency stop. A substantial horizontal deflection occurred under this severe braking condition. The maximum movement was approximately 10 mm, and there was a permanent set of approximately 3 mm. Most of the horizontal displacement and all of the permanent set can

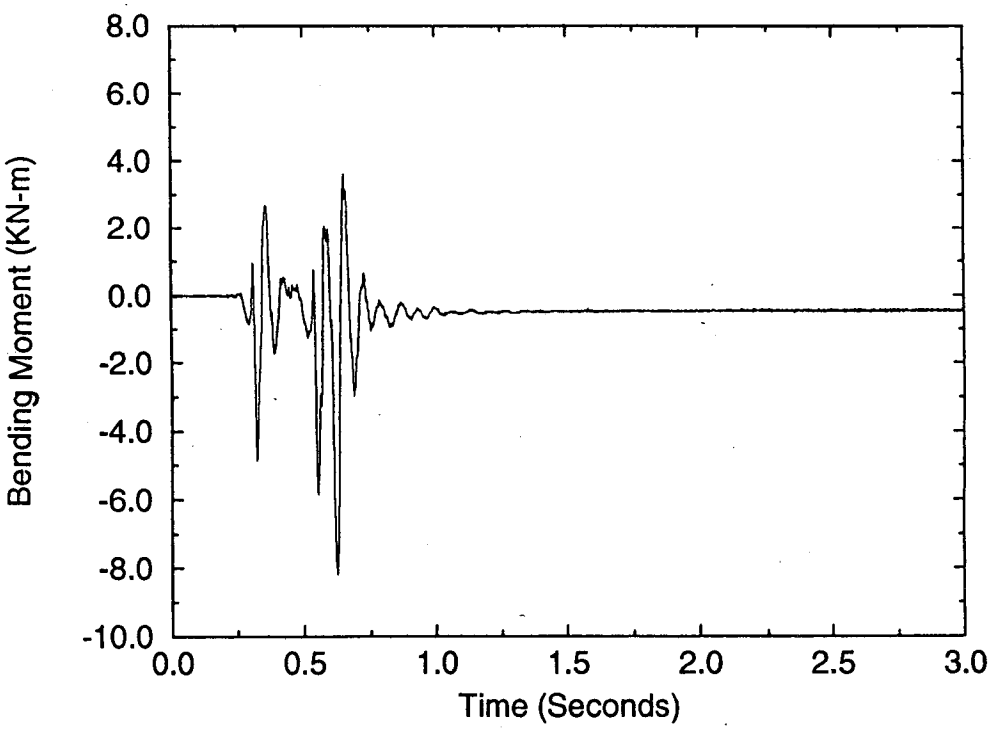

Figure 25. Measured Bending Moment in Centerbeam Due to Horizontal Wheel Loads at 90 kph With Emergency Braking

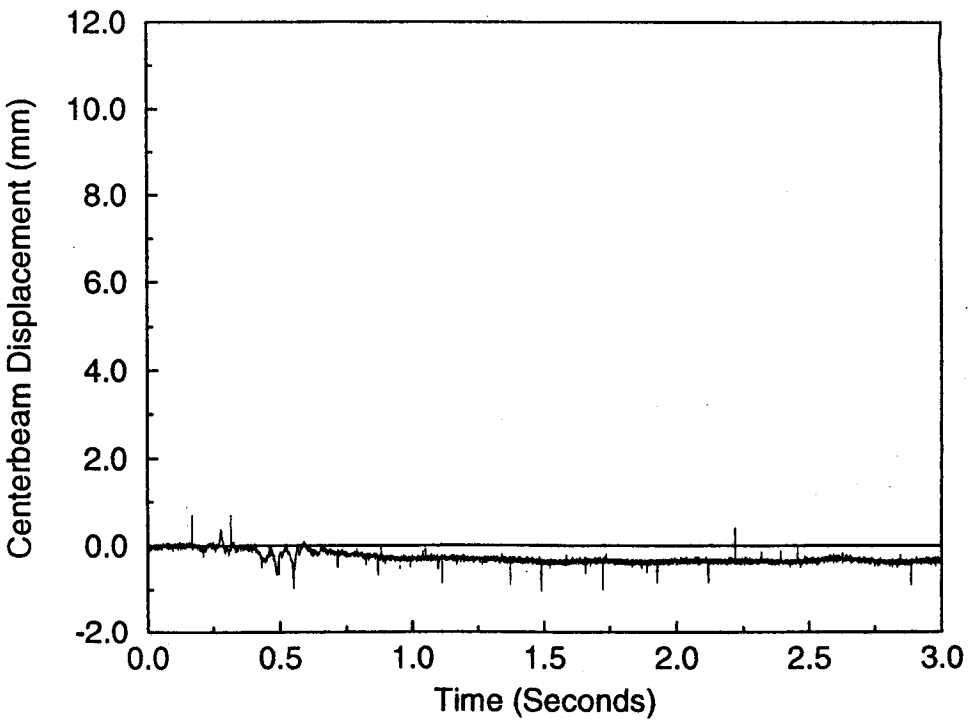

Figure 26. Measured Horizontal Displacement of Centerbeam Due to Horizontal Wheel Loads at 90 kph at Constant Speed

be attributed to rigid body displacement. This is evident by noting that the displacements were essentially the same at mid-span, stirrups, and support bar locations. The permanent set was slowly removed by vibration caused by traffic on the bridge after the truck had passed. The geometry of the joint facilitated the return of the centerbeam to its original position when the joint vibrated. The largest centerbeam movements appeared to occur at slower speeds because of the dynamic characteristics of the joint. This result is consistent with the observations made in analysis that greater dynamic amplification of horizontal loads occurred at slower speeds because the duration of loading more closely matched the longer periods noted for horizontal displacement. The major portion of the deflection was due to deformation and sliding of the elastomeric springs. That is, the centerbeam moved approximately as a rigid body. The elastomeric deflection was elastic and was recovered after the load had been removed, while sliding resulted in permanent set and was not recovered until the normal vibration of the joint had returned the centerbeam to its original position. These measurements indicate that horizontal loads on this particular joint system are significant only when the vehicle is braking or accelerating. This phenomena is consistent with some observations (Braun, 1992) of past joint fatigue behavior, but it is quite different than the event assumed in existing fatigue evaluation procedures.

The direction of travel may also be viewed as important. The joint was on a slight (3 percent to 4 percent) grade, and the normal eastbound traffic had to accelerate slightly to maintain a constant speed. Several measurements were taken with the same truck traveling in the westbound direction. Figure 28 shows the horizontal plane bending moment with the truck traveling in a westerly direction and crossing the joint at a path nearly identical to the one noted for the eastbound truck plotted in Figure 21. The truck did not need to accelerate to maintain its speed in a westerly direction. Comparison of these two figures suggests that the slope did not have a significant effect on this particular joint.

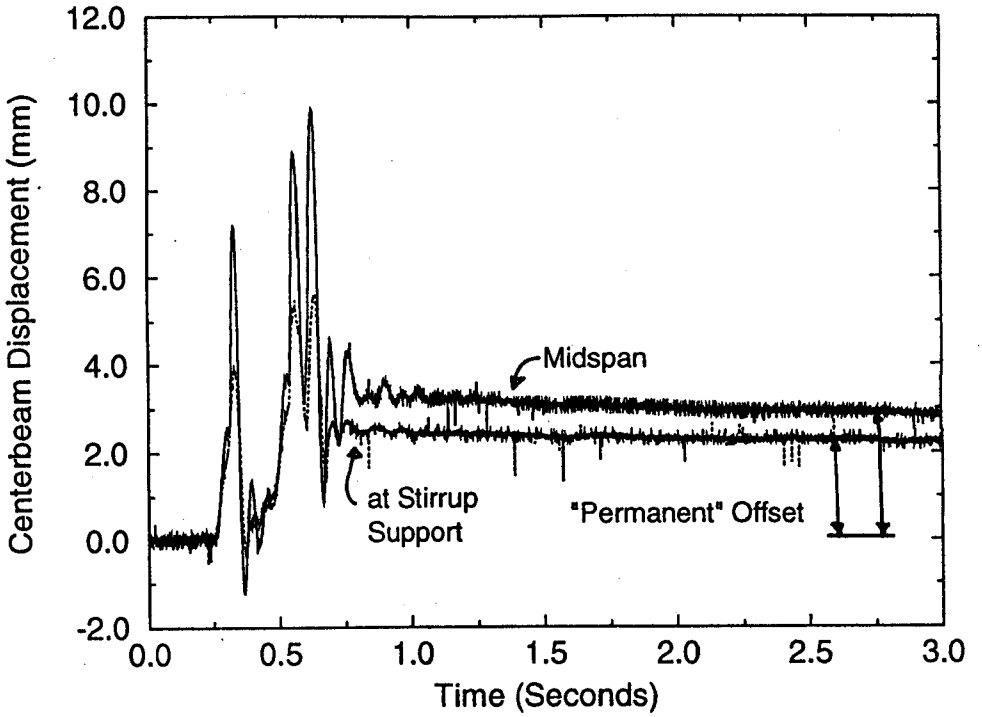

Figure 27. Measured Horizontal Displacement of Centerbeam Due to Horizontal Wheel Loads at 90 kph With Emergency Braking

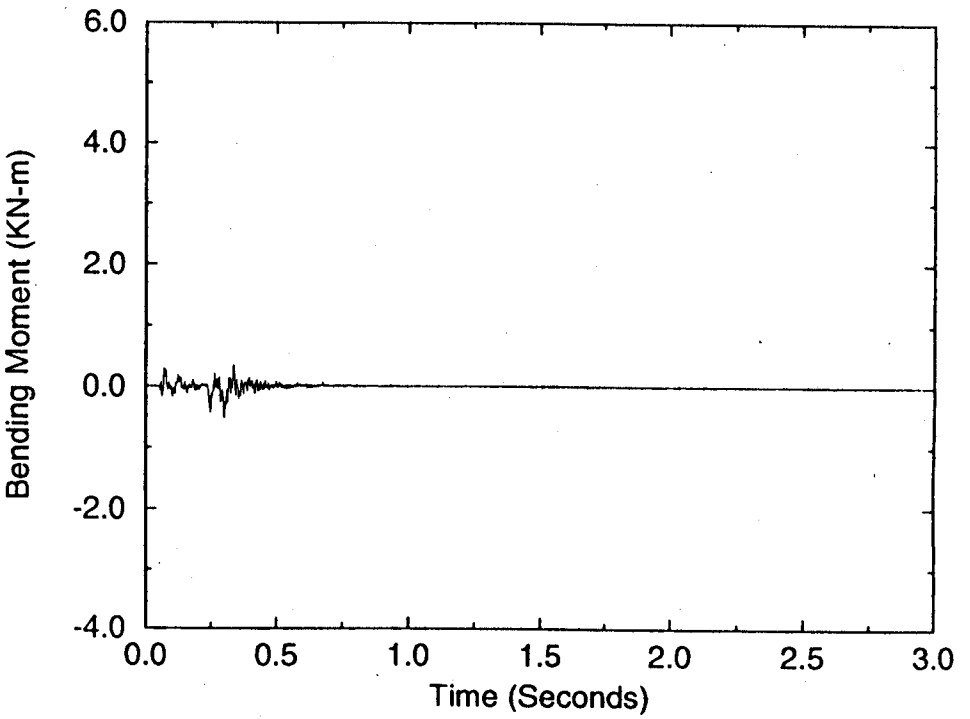

Figure 28. Measured Horizontal Bending Moments of Centerbeam at Midspan Due to a Truck Traveling at Approximately 90 kph in the Westerly Direction

Vehicle acceleration also causes horizontal moments and horizontal displacements of the centerbeam. Figures 29 and 30 show the horizontal plane midspan bending moment and the horizontal deflections of a truck traveling in the eastbound direction at approximately 50 kph and accelerating to gain speed. The figures illustrate that only the rear drive axles caused significant moment and displacement, whereas all wheels of a braking vehicle caused these effects. The moment and displacement were much larger than those noted with the truck crossing the joint at a similar speed without acceleration, but both measurements were much smaller than those noted when a vehicle was braking. The speed of the truck was slower, so the dynamic amplification should have been somewhat larger at this vehicle speed. However, the truck was moderately old and had limited power, and thus it is possible that a more powerful vehicle would have caused a large acceleration effect. Therefore, it is clear that truck acceleration causes a significant effect. It appears that horizontal loads caused by vehicle acceleration are smaller than loads caused by vehicle braking, but this observation can not be proven definitively from these data.

The joint geometry was measured, and the application of Tschemmernegg's distribution model suggested that less than 50 percent of the total wheel load would be applied to a single centerbeam in August, and 50 percent should be appropriate in February. During the load distribution tests, bending moments were measured as a function of time, and typical values of all three curves are plotted in Figure 31. In this figure, the moments are adjusted to account for the difference in span length of the centerbeams; as a result, the moments can be compared at a given time to provide a measure of the portion of load carried by each centerbeam. The figure shows at a glance that well over 50 percent of the wheel load was carried by an individual centerbeam in the February test. When CB13 reached its maximum moment, the moments in CB12 and CB14 were only about 10 percent of that in CB13. As a result, these measurements indicate that a

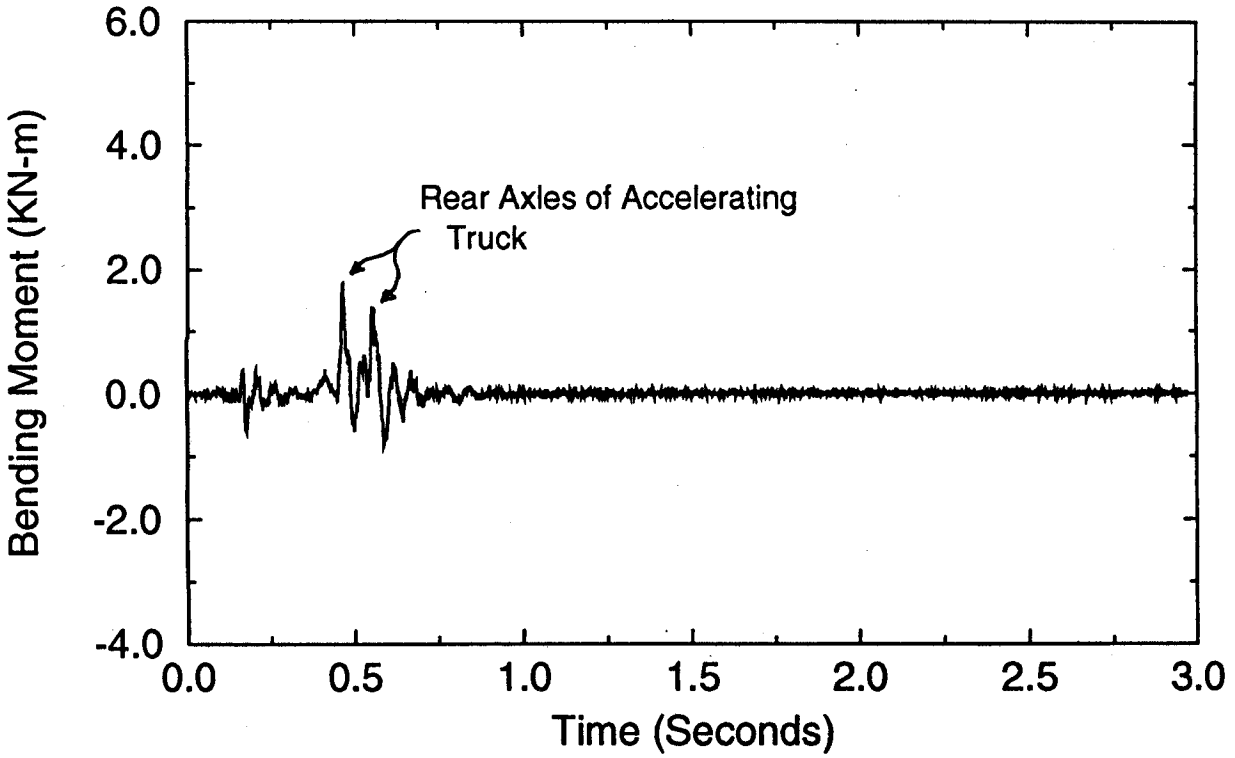

Figure 29. Measured Horizontal Bending Moments of Centerbeam at Midspan Due to a Truck Traveling at Approximately 50 kph and Accelerating

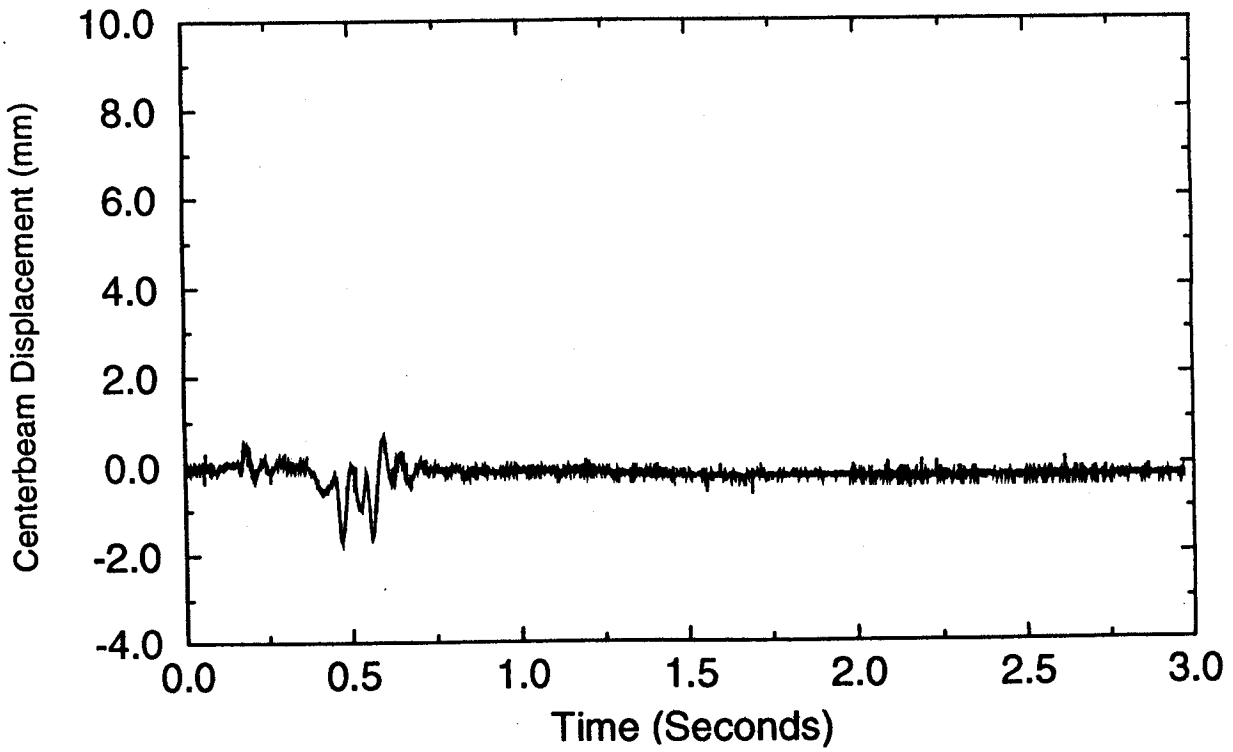

Figure 30. Measured Horizontal Bending Displacement of Centerbeam Due to a Truck Traveling at Approximately 50 kph and Accelerating

maximum of 70 percent to 80 percent of the total wheel load was carried by the single centerbeam. Correlation of these results to the August tests suggested that 60 percent to 70 percent of the wheel load was felt by an individual centerbeam for each wheel crossing.

LOAD SPECTRUM

An examination of the fatigue design load spectrum was one important goal of this research. The uncontrolled truck measurements provided insight into these load data when they were combined with the controlled test results. Figure 4 shows the load spectrum proposed by Tschemmernegg for vertical wheel load and horizontal wheel loads, including impact. This figure shows data provided for approximately 250 billion wheel crossings, but only 25,000 (i.e., 1 out of 10,000) of the these wheel crossings are at the maximum load level. The actual data for formulating Figure 4 are not available, but a graphical interpretation of these data suggest that dynamic vertical wheel loads (including impact) produce the statistical distribution function illustrated in Figure 32. Past analytical studies (Roeder, 1993) have suggested that the Tschemmernegg load spectrum may not be applicable to the subject joint because of the vehicle speeds on the bridge and the dynamic characteristics of the joint. The uncontrolled truck measurements provided a valuable check of the consistency of this design information for the subject modular joint and for U.S. truck traffic.

The dynamic response of nearly 20,000 truck wheel crossings were measured during these uncontrolled tests, and the summary data on the peak response for each wheel, the maximum rebound and free vibration cycles, were developed as described earlier. The peak voltages measured for each wheel crossing were translated into dynamic bending moments, and these moments may theoretically be translated into a dynamic load and vehicle position by means of influence lines. However, only the very heaviest trucks were measured. That is, trucks with vertical dynamic wheel loads of less than approximately 30

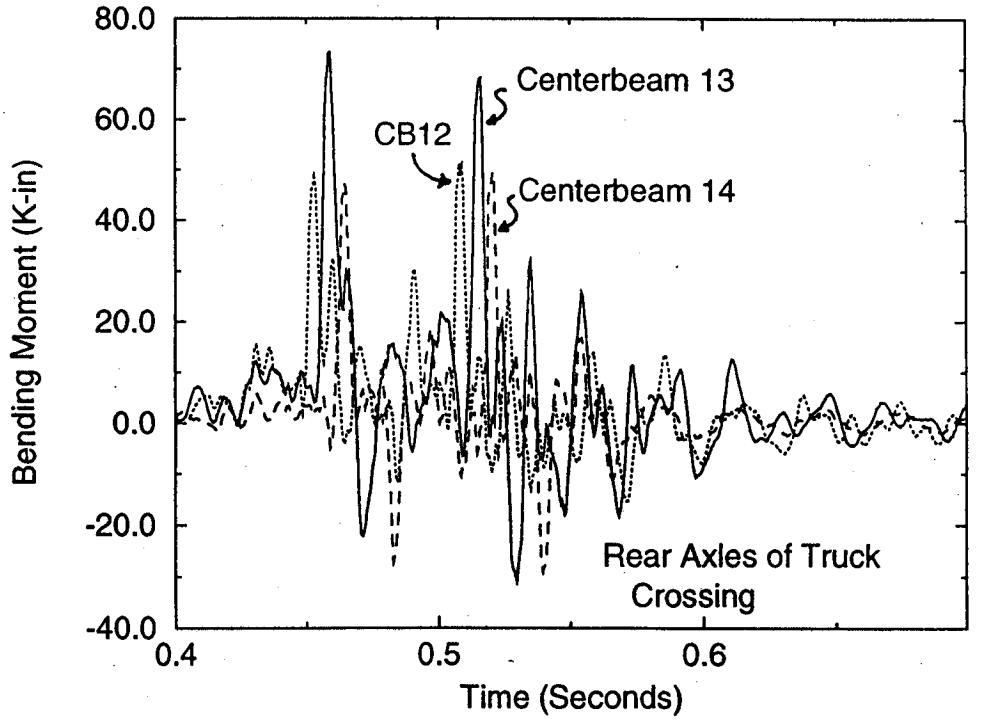

Figure 31. Adjusted Bending Moments on Adjacent Centerbeams and Load Distribution Between Centerbeams

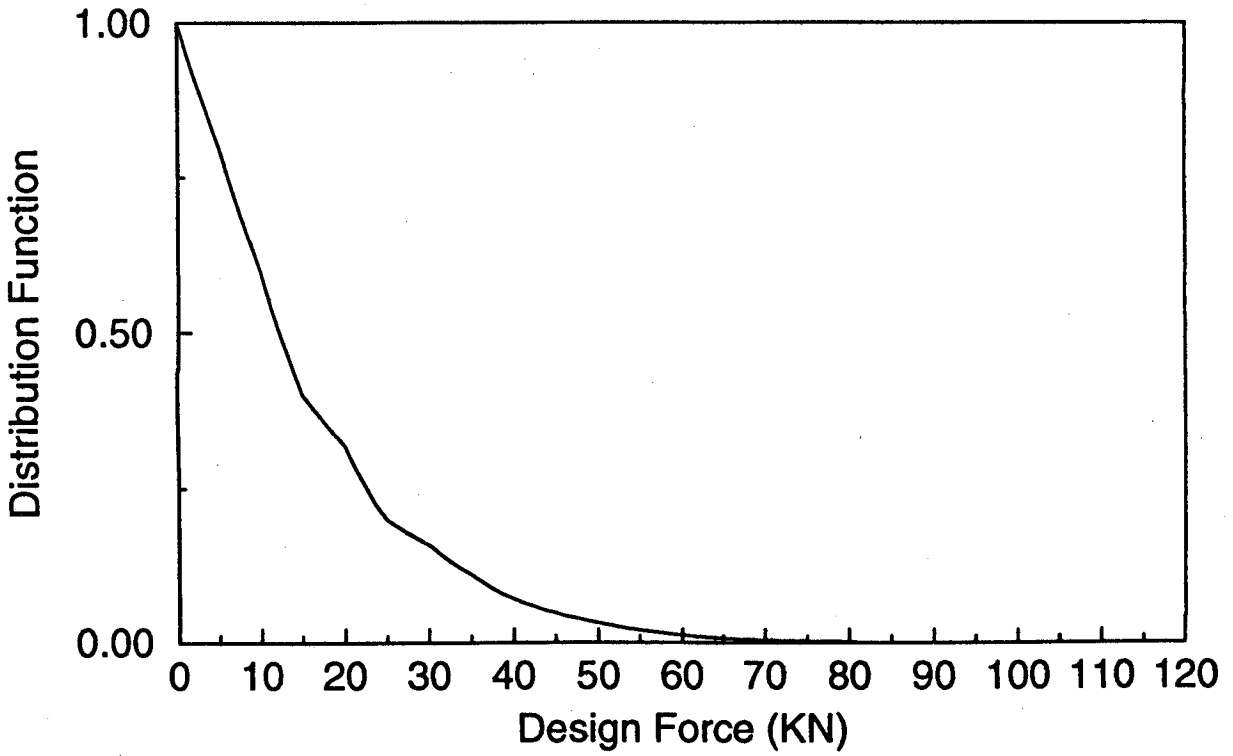

Figure 32. Statistical Distribution Function for Vertical Dynamic Wheel Load from Tschemmernegg Load Spectrum

KN (6.75 kips) were neglected. The Tschemmernegg load spectrum and statistical distribution shown in Figure 4 suggests 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 affected the uncontrolled measurements. None of these variables were known for any one measurement. The speed of the truck affects the dynamic amplification of the static wheel load, as illustrated in Figure 6. With the periods computed and verified by measurements with controlled truck traffic, the vertical wheel loads could be amplified through a wide range of truck speeds, and if the truck speed was estimated with reasonable accuracy, the dynamic amplification could be theoretically estimated with good accuracy. Tschemmernegg (1992) has proposed a method for estimating the load distribution between centerbeams. Prior discussion of the controlled truck measurements revealed that adjustments to load distribution are warranted, but that the load distribution noted by Tschemmernegg clearly is occurring.

While the vehicle speed and load distribution may be estimated by established methods, the vehicle position, geometry, and static wheel loads require additional considerations. Tschemmernegg has proposed that wheel loads be approximated by two point loads that are spaced at a distance appropriate for the centroid of the wheel group for the axle. Measurement of typical truck axles indicated that a spacing of approximately 1.825 m (6 ft) is appropriate for most dual-wheel rear axles. A larger spacing is needed for most front axles or single-wheel rear axles. The largest wheel loads produce the greatest fatigue damage. Thus, the greatest accuracy in the load estimate is required for heavier wheel loads. Further, the heaviest loads are expected on rear axles with dual wheels. Given this 1.825 m (6-feet) wheel load spacing, theoretical influence lines can be developed for the bending moment at each of the measured moment locations. Figure 33

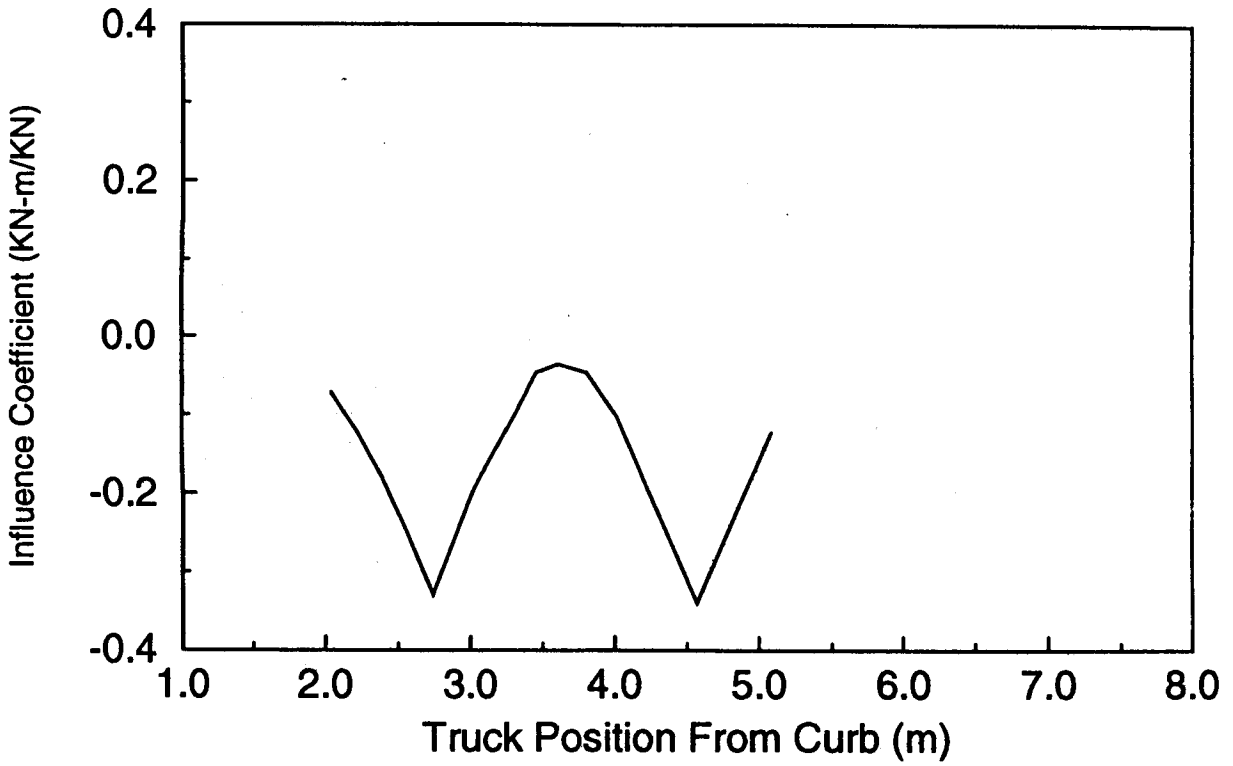

Figure 33. Theoretical Influence Line With Point Loads at 1825 mm (6 ft.)

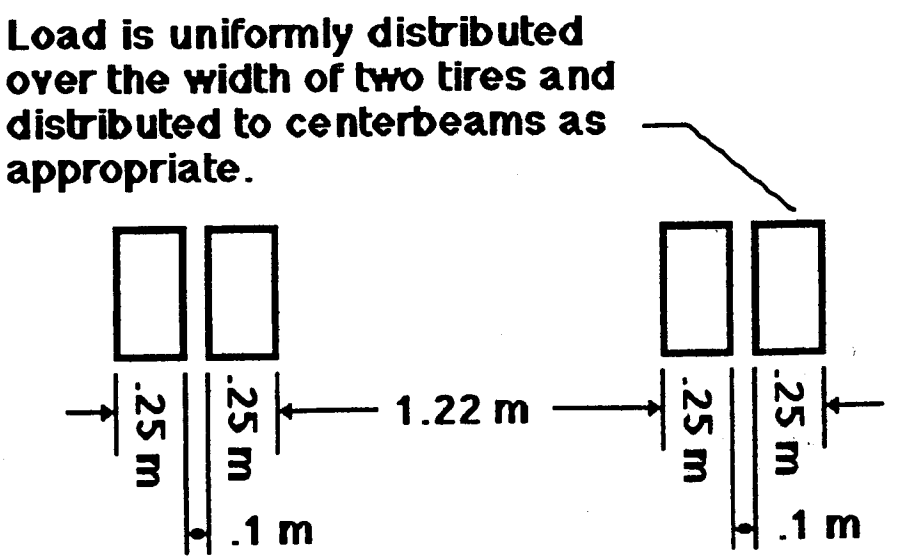

Figure 34. Typical Wheel Load Distribution Geometry for Rear Axle

shows a typical influence line for a vertical load bending moment with equal point loads spaced at 1.825 m (6 ft.). As expected, large increases in measured moments are will occur as one of the wheels is positioned over the measurement location. Magnitudes are smaller when neither wheel is close to the given gage location. The measured moment can be influence lines for four different locations. Any two moment measurements will provide an estimate of vehicle position and dynamic wheel load for that axle crossing for most cases. However, there are also a few singularities. That is, there are locations where the relative magnitude of the moments are the same but the vehicle position has two possible locations. The redundant measurement locations theoretically can be used to determine which position is appropriate under these singularity conditions. Theoretically, these loads and positions can be determined with great accuracy. However, practical constraints limit the accuracy of this load and position determination. Wheel loads are not point loads. Instead they are distributed over an area such as depicted in Figure 34. Influence lines may also be computed when the wheel load is uniformly distributed over this area. Figure 35 shows the influence lines for the 4 measured moment locations, and a comparison of Figures 33 and 35 shows that the curve is nearly identical unless one wheel is positioned very near the measured location. If one wheel is positioned very near the moment measurement location, a narrow tire or single tire will result in a larger measured moment than that predicted by a dual tire with the same total axle loading. The distribution of wheel load across the tire width also reduces the peaks in the influence lines, as can be seen by comparing Figures 33 and 35.

Channels 2 and 3 produced the largest measurements when a truck was centered in the right hand driving lane. It was desirable to use the larger measurements for load determination, since they would provide greater sensitivity and fewer concerns regarding measurement accuracy. Therefore, the researchers proposed that Channels 2 and 3 be the primary channels for estimation of vehicle position and wheel load. Channels 1 and 4 were

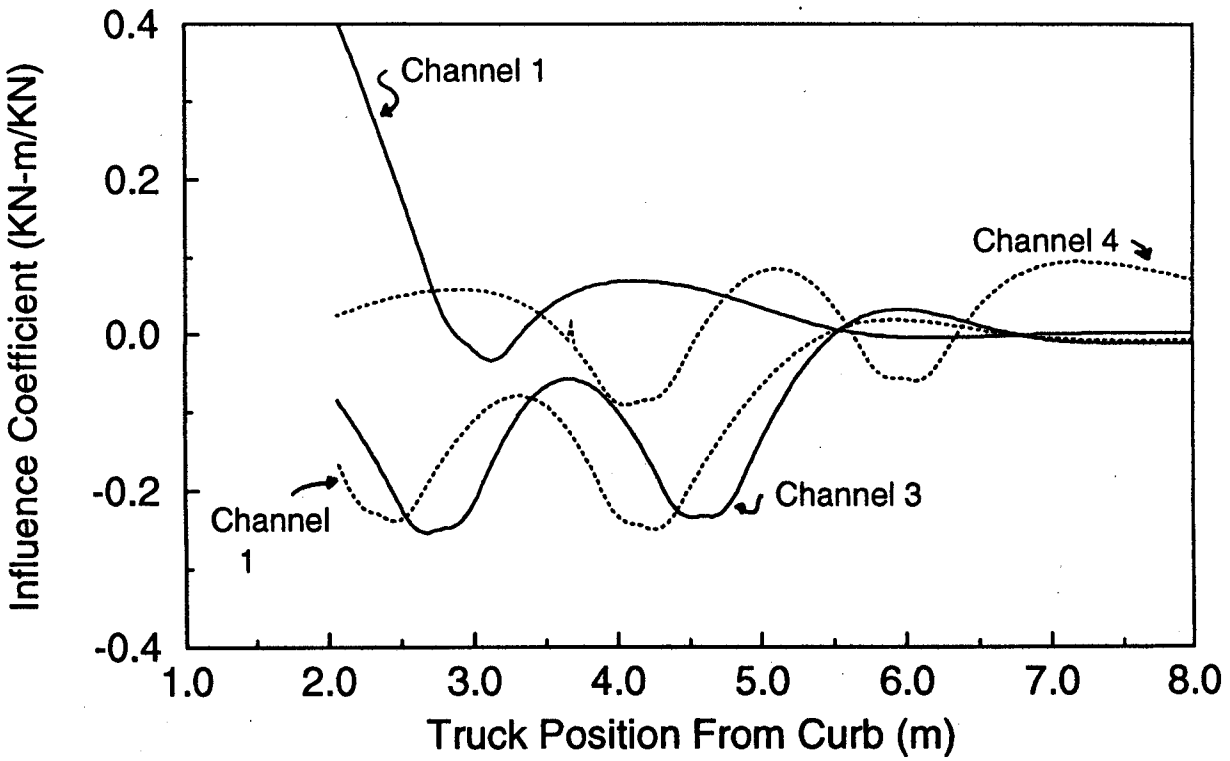

Figure 35. Theoretical Influence Lines for Moment Measurement Locations 1 Through 4 With Distributed Wheel Loads

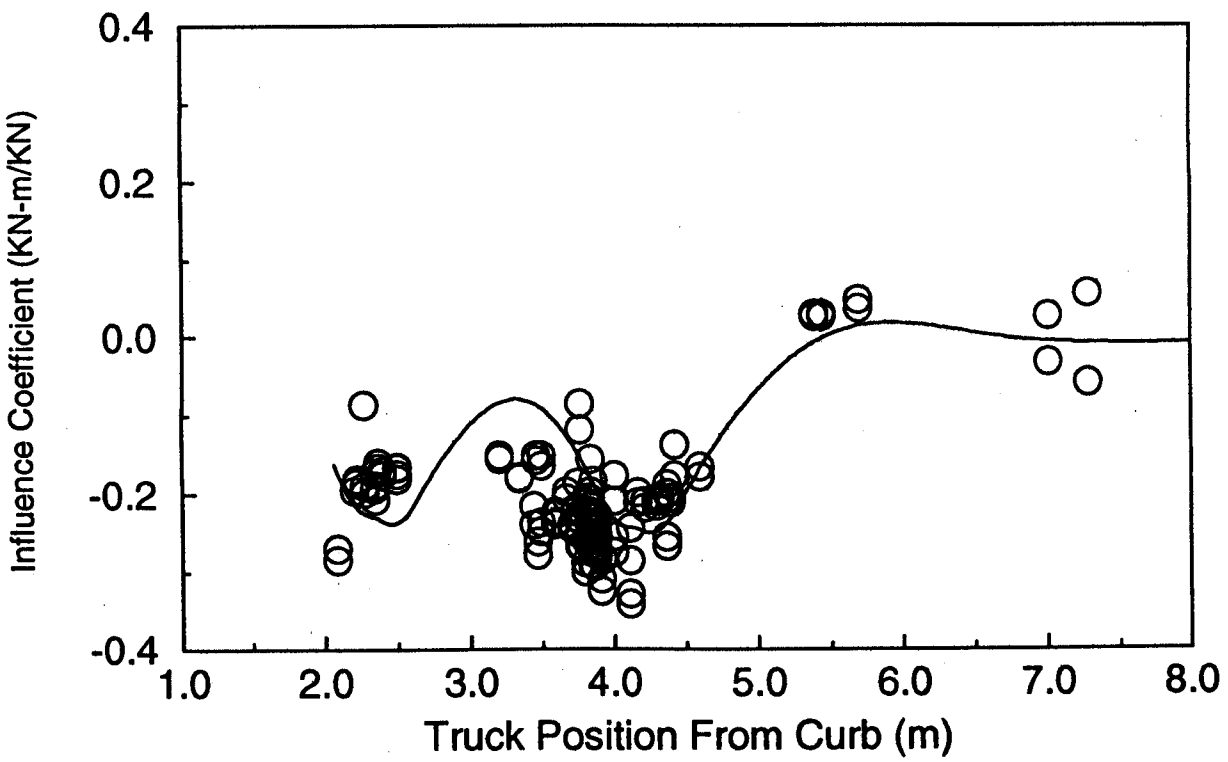

Figure 36. Measured Moments Divided by Static Wheel Load for Measured Moment 2 for all Controlled Test Rear Axle Measurements

to be used for resolution of singularities or other uncertainty. The controlled vehicle measurements provided a general check of this proposed procedure, since the speed, geometry and position of the vehicle were known with reasonable accuracy. Note that the geometry and static loads of the controlled vehicle were known to the highest accuracy, while speed was known only within an accuracy of $\pm$ 5 kph ($\pm$3 mph). Possible positioning errors of up to 50 mm (2 inches) had to be expected. The positioning errors were caused by the fact that individual vehicle wheels may have crossed the joint at slightly different positions during a given truck crossing, as well as by uncertainty of the measurement itself. Figures 36 and 37 show the measured moments for all measured rear axle crossings divided by the known static load, plotted along with the influence lines for distributed wheel loads for Channels 2 and 3. These illustrate that the general trends of the measured values follow the computed influence line, but there is a huge amount of scatter in the results.

Some of the scatter shown in Figures 36 and 37 had to be expected, as the measured data were a dynamic response. This dynamic measurement included possible amplification and attenuation, and it did not include load distribution between centerbeams. The speed of the vehicle and the dynamic periods of the joint components were known, and so the measured dynamic wheel load could theoretically be converted to a measured static wheel load by dividing by the amplification factor predicted in Figure 6. The measurements wheel load distribution between centerbeams varied from August 1993 to February 1994. However, they should have been nearly constant during those two time periods. The dynamic amplification and load distribution corrections were made to the data to obtain measured static moments. The measured normalized, static moments and influence lines are plotted in Figures 38 and 39. Considerable scatter remains, but the results much more consistently match the influence line predictions. Despite the improved comparison, the theoretical influence lines were still not adequate for accurately placing the

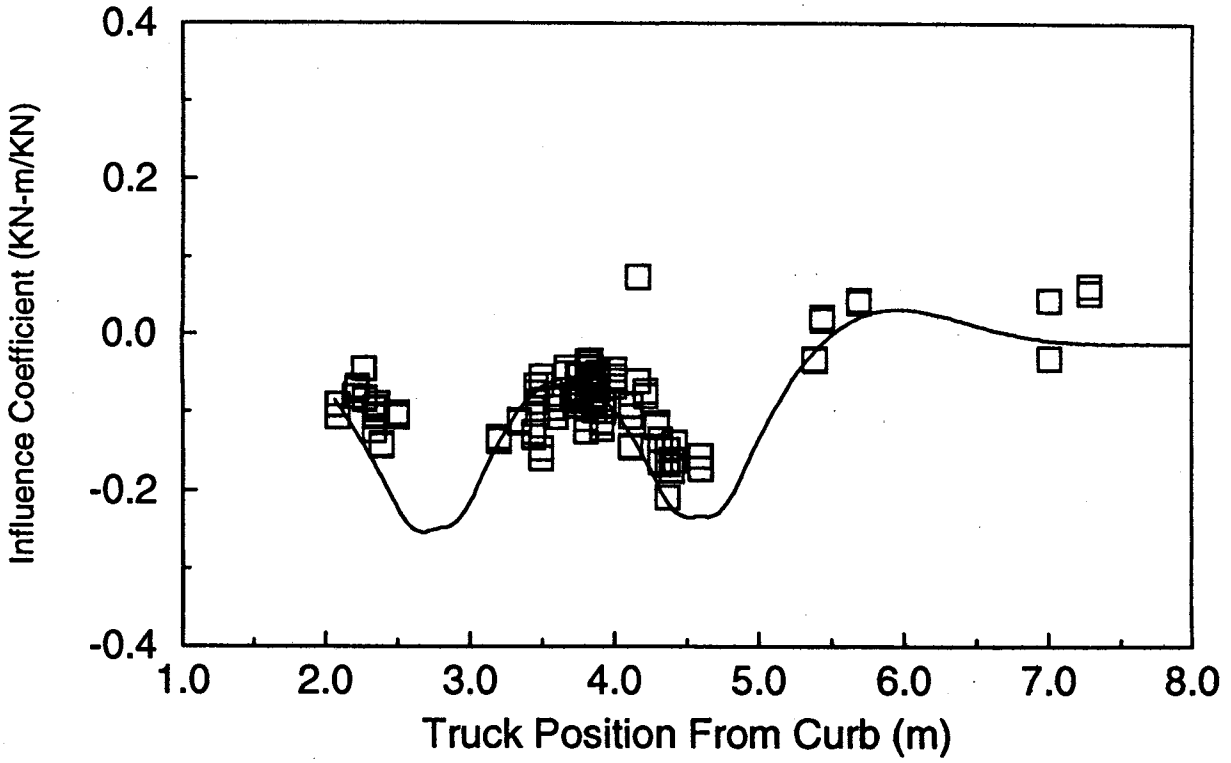

Figure 37. Measured Moments Divided by Static Wheel Load for Measured Moment 3 for all Controlled Test Rear Axle Measurements

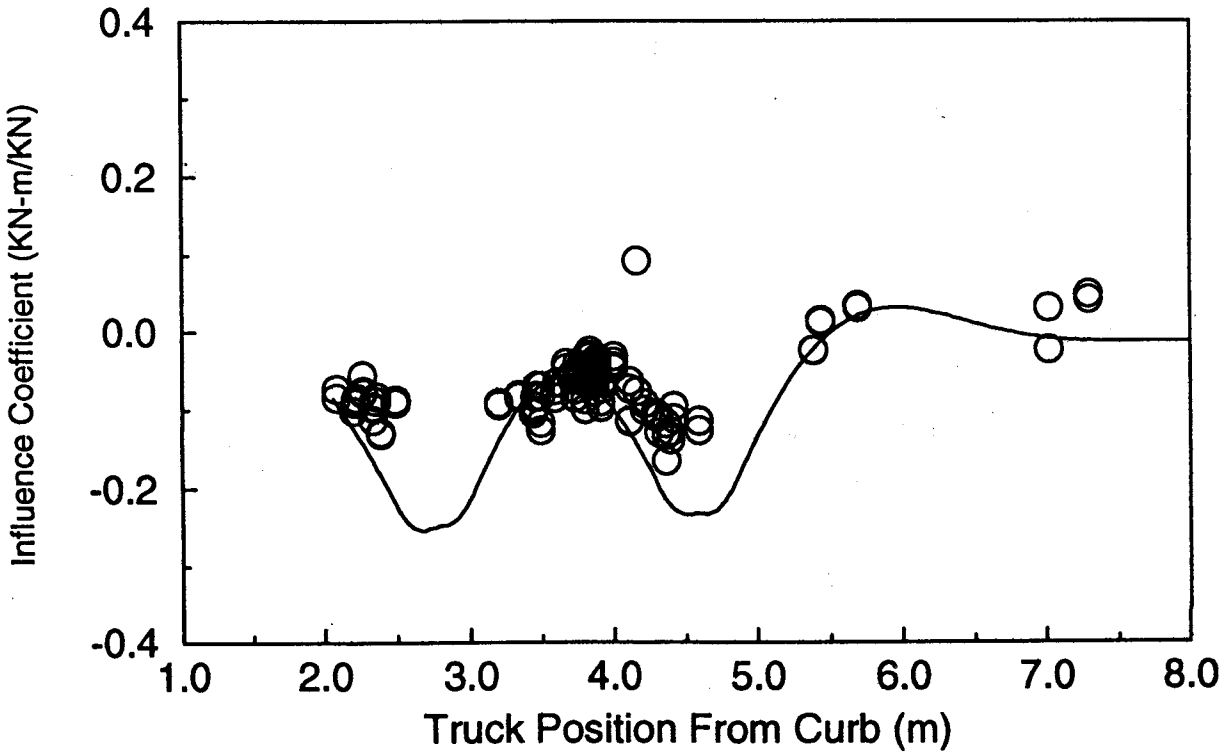

Figure 38. Corrected Normalized Measured Moments Divided by Static Wheel Load for Location 2 for all Controlled Test Rear Axle Measurements

position of the vehicle and establishing the wheel load magnitude. Averaging procedures would improve this estimate. These averaging procedures are illustrated in Figure 40 for the vehicles within the right lane of traffic.

The normal value for Figure 40 should be 1.0. The scatter about this value is quite uniform, although it is skewed toward the edges of the driving lane. Examination of Figures 38 and 39 and comparison of the theoretical influence line to the measured data show that the characteristics of the measured data were close to the influence line, although there was an offset of the data in both cases. Figure 38 suggests that a better and quite good comparison would be achieved if the theoretical influence were shifted 10 to 15 inches to the left. Figure 39 suggests a better comparison if the theoretical influence line were shifted approximately 10 inches to the right. Changes in the stiffness of the elastomeric springs and other elements could have caused changes of this type in the influence lines, but there is no rational theoretical basis for changing these stiffness values except that they fit the experimental data better. However, a significant body of experimental data with known conditions exists, and these data could form the basis for empirical influence lines.

Figure 41 illustrates one formulation of the empirical data for trucks in the right lane with a least squares fit curve for the data. Empirical relations such as that illustrated in Figure 41 were examined in some detail, and several factors were noted. First, trucks that were approximately centered in the right hand driving lane produced results that were relatively insensitive to position. That is, a substantial variation in position caused relatively small changes in load estimate. Note that an influence line position of 3.3 m (130 in.) had the right wheel over the white line on the right edge of the lane. An influence line position of 4.6 m (180 in.) had a left wheel crossing the white line into the center lane. Second, vehicles that were outside the center of the travel lane were easy to identify because of the larger moments measured at channels 1 or 4 and the moment reversal noted

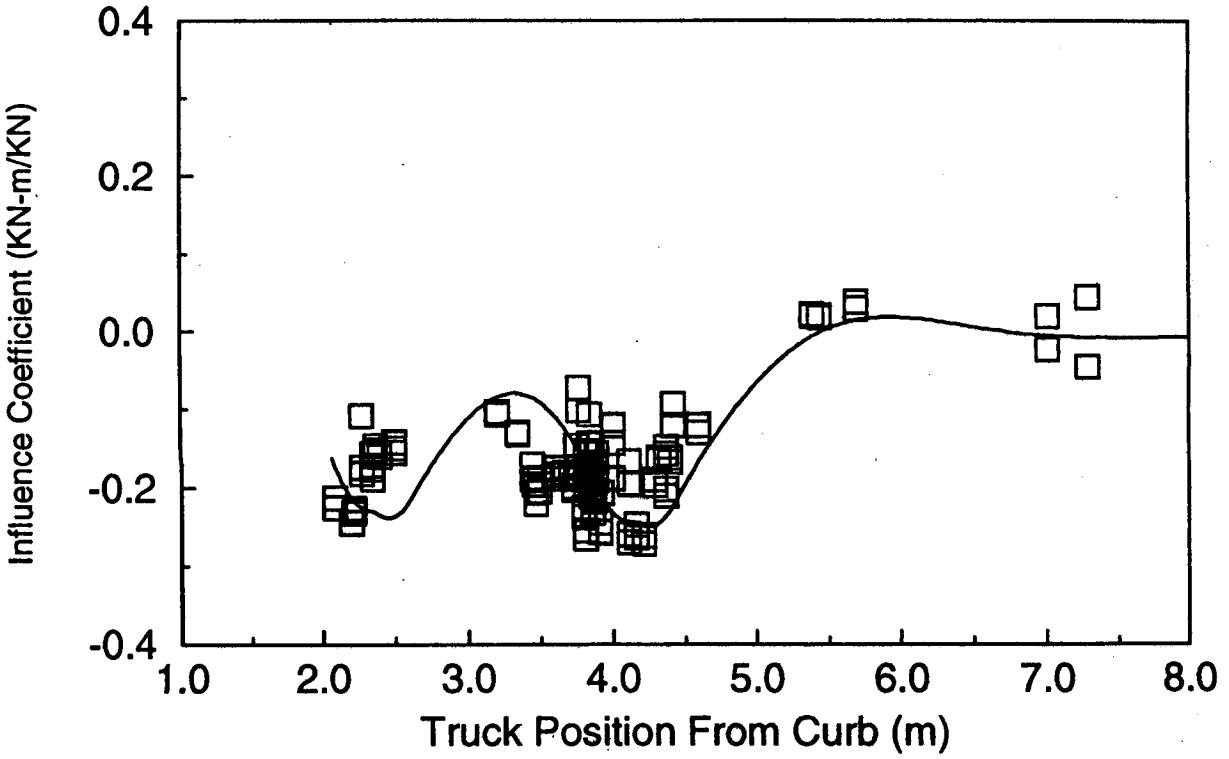

Figure 39. Corrected Normalized Measured Moments Divided by Static Wheel Load for Location 3 for all Controlled Test Rear Axle Measurements

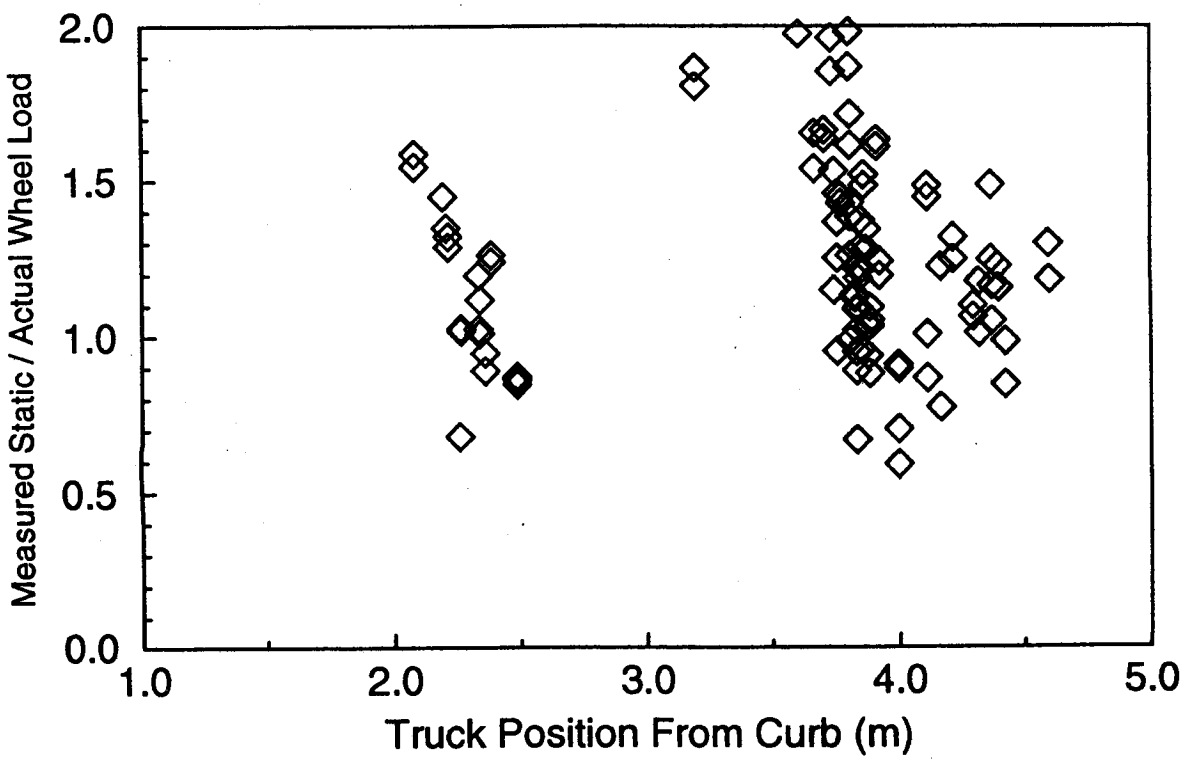

Figure 40. Averaged Estimate of Measured Static Wheel Load Divided By The Actual Wheel Load

at channels 2 or 3. Finally, the scatter produced by efforts to isolate the vehicle position was greater than the scattered produced by assuming the truck was in the center of the marked driving lane, if the data for trucks driving outside the lane were excluded.

As a result of this analysis, the 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. Figures 42, 43, and 44 show the histograms of these data. These are dynamic wheel loads that consider the distribution of load between centerbeams. For these curves, 60 percent of the wheel load was estimated to act on the individual centerbeam rather than the 50 percent postulated by the Tschemmernegg method because of the greater load distribution to individual centerbeams noted during the controlled tests. Examination of these histograms shows that only vehicle wheel loads greater than 30 kn (6.7 kips) were recorded, but a substantial number of vertical wheel loads exceeded the dynamic wheel load of 91 KN (20.4 kips) proposed by Tschemmernegg. A substantial number of vehicles also exceeded the rebound load spectrum design value of 27.3 KN (6.1 kips) proposed by Tschemmernegg. Even larger statistical wheel loads would result if the 50 percent load distribution had been employed. Very few vehicles exceeded the 18.2 KN (4.1 kips) horizontal load proposed by Tschemmernegg. The horizontal loads were computed under an assumption of stiff supports, and as a result, the true horizontal wheel load was overestimated. However, this statistical variation would be appropriate if the same stiff boundary conditions also were used in conjunction with the wheel load estimate.

The Tschemmernegg design load spectrum was graphically analyzed to obtain a cumulative distribution function. The distribution function shows the probability that a given dynamic wheel load will be exceeded. These distribution functions were plotted. In addition, the researchers noted that Tschemmernegg's data indicated that only the largest 16 percent of wheel loads were measured in this study, and so these measured data were also

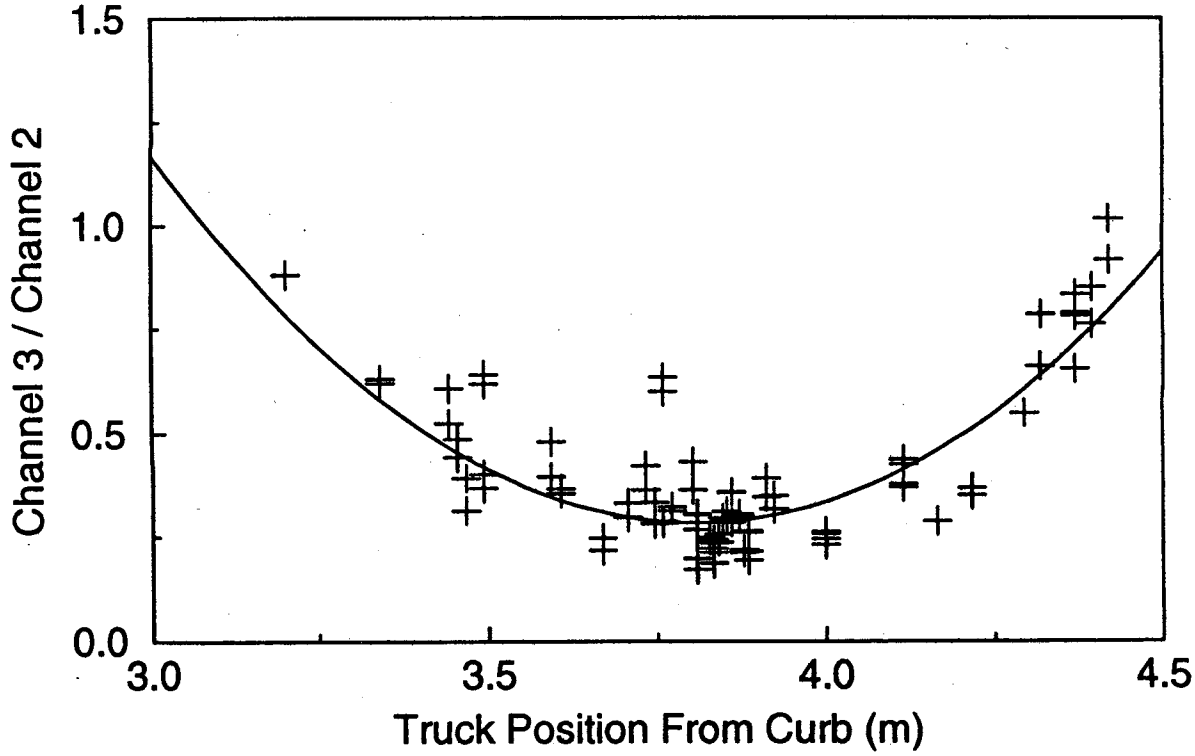

Figure 41. Empirical Influence Line Representation and Comparison to Controlled Test Experimental Results Based on Channel 2 and 3

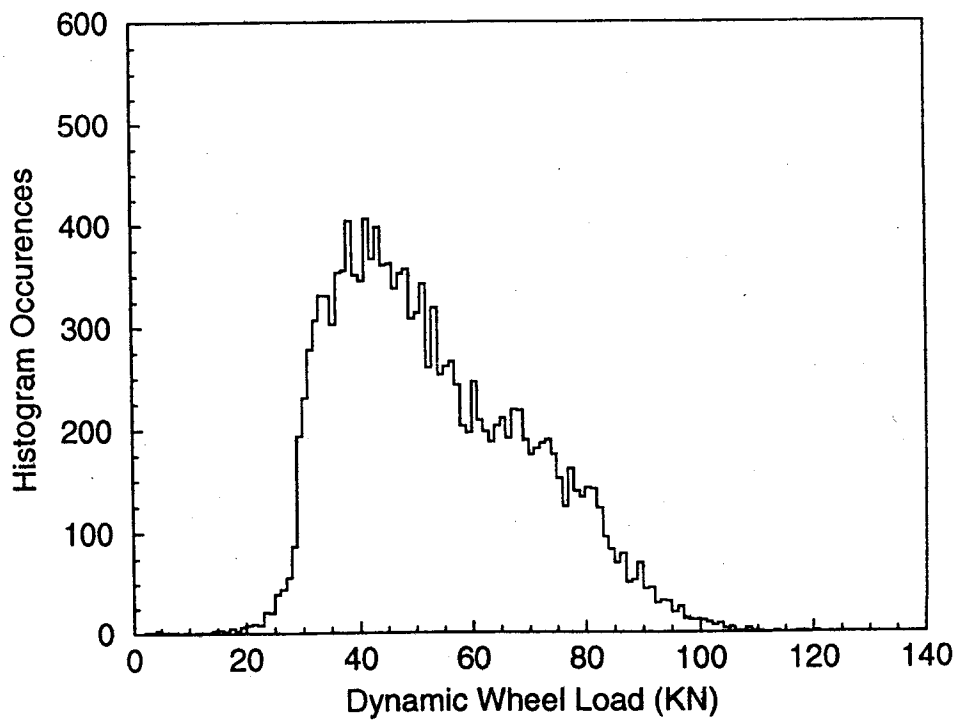

Figure 42. Histogram of Measured Dynamic Wheel Loads Due to Vertical Dynamic Impact Loading

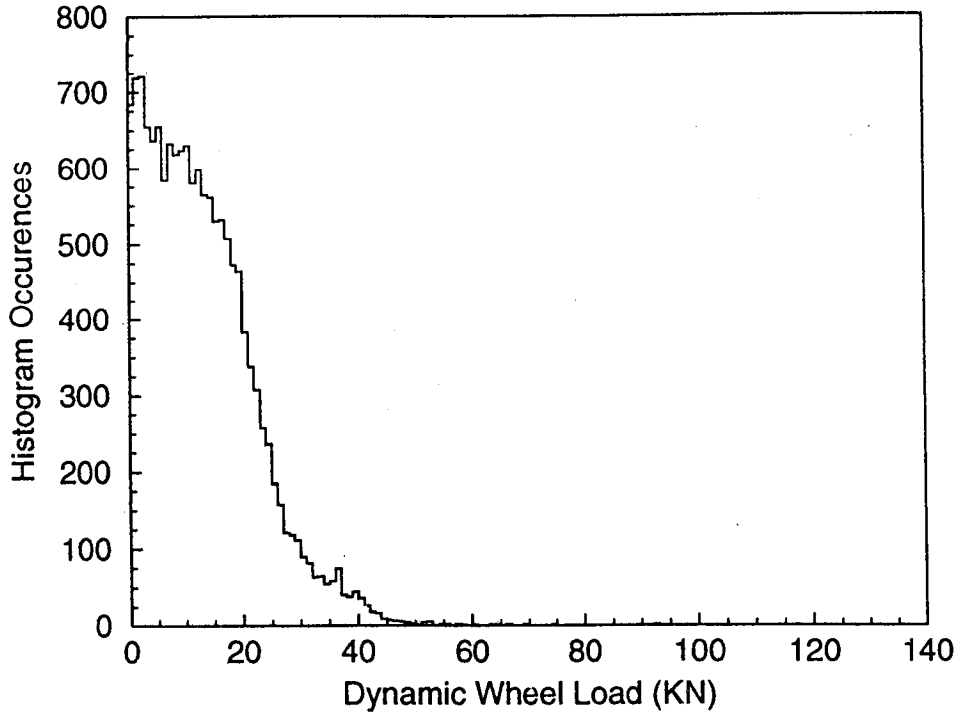

Figure 43. Histogram of Measured Dynamic Wheel Loads Due to Vertical Rebound Due to Dynamic Loading

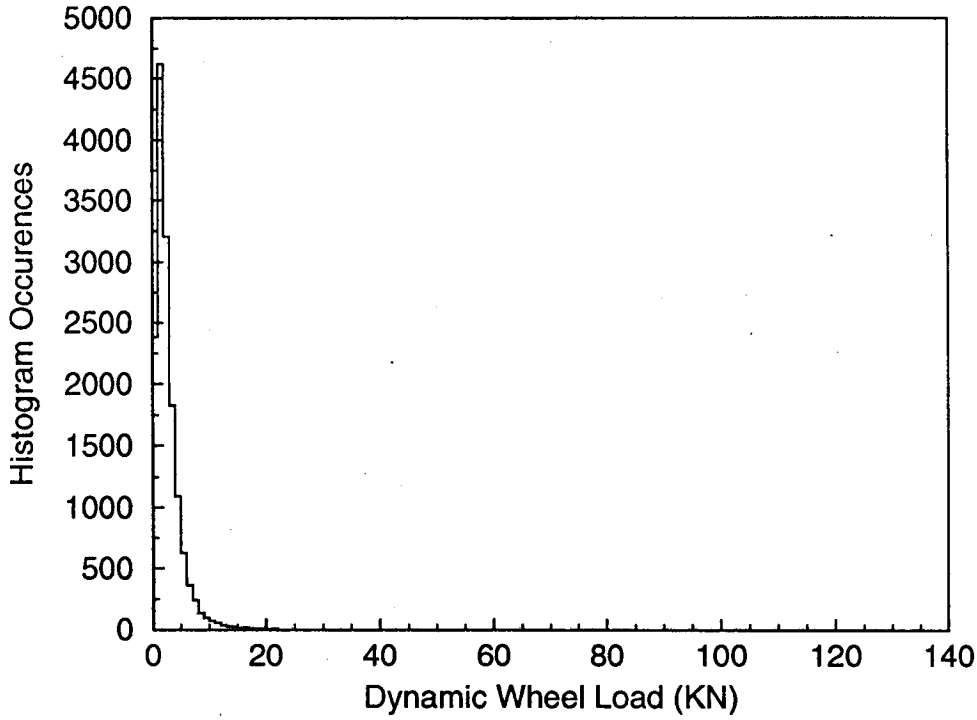

Figure 44. Histogram of Measured Dynamic Wheel Loads Due to Horizontal Dynamic Loading

translated into a partial distribution function for vertical impact loading and horizontal loading. These curves are shown in Figures 45 and 46. These figures quite clearly show that a much larger proportion of vehicles were causing large, vertical dynamic loads on the modular joint than predicted by the Tschemmernegg method. A much smaller proportion of vehicles were causing large, horizontal dynamic loads on the modular joint than predicted by the Tschemmernegg method. This difference may be partially attributed to a larger portion of the loading experienced by an individual centerbeam. That is, a 70 or 75 percent distribution would improve the comparison between the experimental and Tschemmernegg's vertical impact and rebound wheel load spectra. However, poorer comparison between the two spectra would result for horizontal loading. As a result, much of the difference must be related to dynamic characteristics of the joint. This modular joint system amplifies the dynamic response for a wide range of vertical load conditions. Horizontal loads are attenuated through a large range of vehicle speeds. At the same time, normal traffic produces very few vehicles that brake hard or accelerate as they cross the joint. Future changes in traffic patterns could change these traffic characteristics, since slower vehicle speeds or increased vehicle braking could significantly increase the horizontal load effect. The statistical variation in rebound loads appears to be similar to that noted for direct vertical loading.

DESIGN RECOMMENDATIONS

Recommendations for design loads were developed from the experimental evaluation. However, it must be emphasized that the design loads are very sensitive to the type of joint and traffic patterns. Joints that are stiffer with respect to horizontal loads should be designed for larger horizontal loads. Further, traffic patterns that produce a larger amount of braking and accelerating than observed during this research must also cause larger horizontal forces.

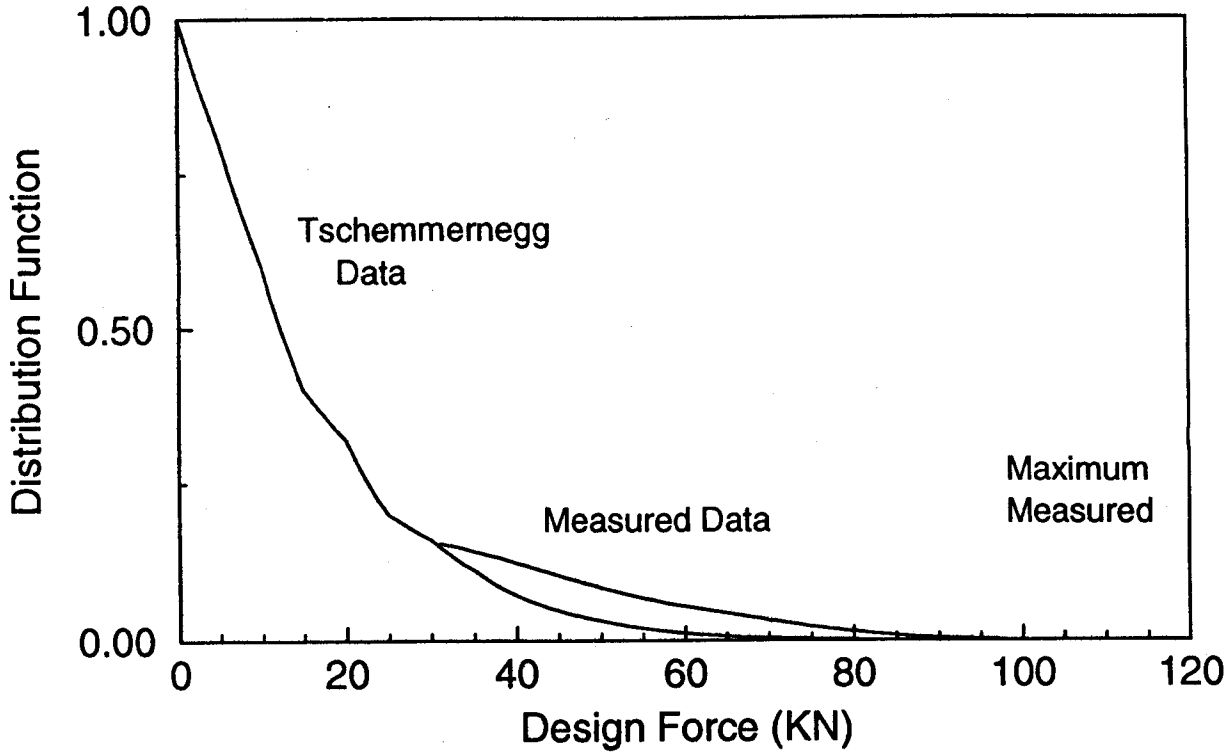

Figure 45. Cumulative Distribution Functions For Vertical Dynamic Wheel Loading

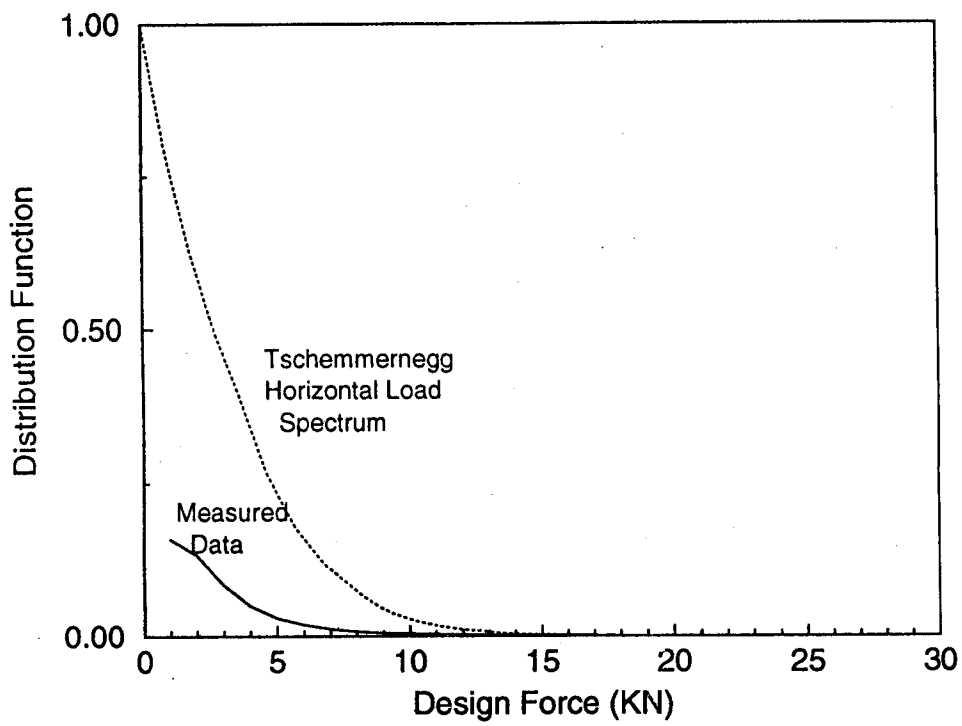

Figure 46. Cumulative Distribution Functions for Horizontal Dynamic Wheel Loading

For the swivel single support bar system studied in the research, a substantial number of measured vertical wheel loads were larger than those reported by Tschemernegg. However, fewer and smaller horizontal loads were measured than reported by Tschemmernegg. Larger loads cause the greatest amount of fatigue damage. Therefore, it is recommended that the vertical dynamic wheel load be increased to 110 KN (24.7 kip). The vertical rebound load should be increased to 45 KN (10.2 kips). When these increased vertical loads are employed, it is appropriate to recognize the smaller horizontal loads present in the joint. Therefore, a horizontal load of 10 KN (2.2 kips) is suggested for this joint system and traffic pattern. These recommendations are summarized in Table 2.

Note that these measurements suggest that a larger portion of the individual wheel loading is supported by a single centerbeam than is suggested by the Tschemmernegg method. Therefore an increase should be applied to the Tschemmernegg method. The increase should be approximately 10 percent of the wheel load for all spacing conditions. For example, a distribution factor of 0.6 should be used when the Tschemmernegg procedure calls for a 0.5 distribution.

The combined effects of these recommendations will increase the conservatism of the fatigue design and result in heavier centerbeams. However, this appears to be a small price to pay in comparison to the cost of early replacement of the joint system.

Table 2. Design Recommendations

	Recommendations From This Research	Recommendations From Tschemmernegg Procedure
Direct Vertical Dynamic Load	110 KN (24.7 kips)	91 KN (20 kips)
Rebound Vertical Dynamic Load	45 KN (10.2 kips)	27.3 KN (6 kips)
Positive Horizontal Dynamic Load	+10 KN (+2.2 kips)	+18.2 KN (+4 kips)
Negative Horizontal Dynamic Load	-10 KN (-2.2 kips)	-18.2 KN (-4 kips)
Load Distribution to Centerbeams	0.1 + Tschemmernegg Graphical Procedure	Tschemmernegg Graphical Procedure Provided

SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

SUMMARY

This study examined the performance of modular expansion joints under field conditions. The single support bar modular system on the third Lake Washington floating bridge was instrumented to measure strains, moments, loads, and deflections under truck traffic. Controlled tests were performed with a truck of known wheel loads and driving conditions. The results were analyzed, and important conclusions regarding the behavior of this joint system were drawn from these tests. Additional measurements were performed with normal truck traffic crossing the bridge. Approximately, 20,000 vehicle wheels were recorded. These wheels constituted the heaviest 16 percent of vehicle wheel loads expected on a modular joint. These tests provided valuable information regarding the fatigue design loads for modular expansion joints.

CONCLUSIONS

The most important conclusions drawn from the research include the following.

1. The experimental observations, including stiffness and periods of vibration, were consistent with theoretical calculations made in an earlier study.

2. The vertical loading due to direct impact of a truck is amplified through a wide range of vehicle speeds, with dynamic amplification of about 50 percent expected at normal interstate vehicle driving speeds.

3. The vertical rebound load is larger with higher speeds and smaller with slower traffic.

4. The horizontal loads under ordinary traffic on this particular modular joint system are much smaller than those suggested by the Tschemmernegg fatigue design method because of the flexibility and potential for slip noted with this type of

modular joint. This is consistent with the theoretical calculations indicating that joint behavior is very dependent upon the joint type.

5. Bending moments due to horizontal loads under vehicle braking may be very large. These moments may exceed those suggested by the Tschemmernegg fatigue design method.

6. Horizontal movements occur in the joint when braking vehicles cross the joint. The movements are quite large and involve multiple spans of centerbeam and they incorporate shear deformation of the elastomeric springs and sliding of the low friction surfaces. A portion of the movement is not immediately recovered, but the centerbeam returns to its original position only after vibration of the joint caused by normal traffic. The largest horizontal bending moments are not caused by larger horizontal forces. Instead, these largest moments can be attributed to increased effective span lengths in the centerbeam caused by rigid body movements. However, the movement places a significant limit on the maximum horizontal force that the joint components may experience.

7. Load distribution between centerbeams was 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.

8. The experimental load spectrum obtained during a three-week period in late August and early September 1993 showed a larger number of larger dynamic wheel loads for vertical impact and rebound than suggested by the Tschemmernegg procedure.

9. The experimental load spectrum obtained during the three-week period showed a smaller number of maximum horizontal loads than that suggested by the Tschemmernegg procedure.

10. The dynamic loadings on modular expansion joints are very sensitive to the characteristics of the joint. These characteristics include the stiffness under both vertical and horizontal loading.

11. The dynamic loading on modular expansion joints is also very sensitive to traffic patterns. Slower (or faster) vehicle speeds and increased (or decreased) braking or acceleration of vehicles crossing the joint may dramatically change the expected load history and fatigue life.

RECOMMENDATIONS

Several recommendations can be made because of these experimental observations. These include the following.

1. The dynamic loads on modular expansion joints are very sensitive to traffic conditions, wheel loads, and dynamic characteristics of the joint. Changes in these parameters, such as decreased vehicle speed or increased braking and acceleration of vehicles as they cross the joint, may dramatically change the dynamic loads and fatigue life of the joint system.

2. The vertical fatigue design loads for modular joints of this type, including dynamic impact, should be larger than those recommended by the Tschemmernegg procedure. The direct vertical load should be increased to 110 KN (24.7 kips). Also, the rebound load should be increased to 45 KN (10 kips). The dynamic properties of the joint, combined with the traffic patterns, result in greater amplification of the vertical load effects.

3. Individual centerbeams feel a somewhat larger portion of the wheel load than suggested by the Tschemmernegg method. Therefore, the Tschemmernegg distribution ratio should be increased by 0.1.

4. The horizontal fatigue design loads for modular joints of this type may be much smaller than required in the Tschemmernegg method. It is suggested that

these loads be decreased to 10 KN (2.2 kips) if the above vertical load increases are employed. However, it must be recognized the these horizontal loads may be much larger in the future if traffic patterns on the bridge and the joint change.

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