APPLICATIONS OF A BRIDGE MEASUREMENT SYSTEM

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Recent efforts to record bridge strain histories due to highway truck traffic have been prompted by modifications in fatigue code, introduction of high-strength steel alloys and more fatigue-sensitive welded bridge details, and increases in truck weights and volumes. This study was designed to improve measuring and processing systems and to expand both the amount and the type of information recorded in bridge studies. Truck headway and type, lane location, and corresponding strain record and maximum stress range were recorded and processed on 10 slab-girder bridges for almost 20,000 truck passages. This paper describes the measurements and processing system developed and discusses applications of the measurement data to fatigue design including impact, girder load distribution, fatigue life stress cycles, predicted and measured stresses, and the potential for weighing trucks in motion on bridges.

•DURING the last 20 years, as measurement equipment has been improved and interest in the fatigue of bridges has increased, many studies have been reported of field measurements of highway bridges (1, 2). These studies recorded strain due to random truck passages at various bridge girder locations. Such data have been used to plot histograms of peak stress ranges expected over the lifetime of a bridge. From such field data and laboratory information on fatigue behavior of bridge elements, estimates have been made of fatigue life.

In the last few years there has been even further impetus for recording strain histories. Bridge measurement studies have been conducted in Illinois, Connecticut, Virginia, Maryland, Michigan, Pennsylvania, Indiana, Alabama, Tennessee, Missouri, other states, and Canada (3 through 11). These studies have been sparked by modifications in fatigue codes, introduction of high-strength steel alloys and more fatigue-sensitive bridge details, rapid growth in truck weights and volumes, and several instances of reported bridge fatigue cracks.

This study was designed to improve the state of the art in measurement systems by expanding both the quantity and the type of information recorded in a bridge study. A shortcoming of most of the reported field studies has been the difficulty of accumulating large numbers of bridge strain records. In early work the data were recorded on an oscillograph, and converting this record to a usable digital form either was slow and tedious or required very expensive record analysis equipment (3, 4). Some recently developed measurement systems use magnetic tape, but expensive data processing systems in some cases have made it necessary to turn off the tape recorder between truck crossings. Hence, the systems cannot be used on arteries that have large volumes of truck traffic. The FHWA system on the other hand used a magnetic tape recorder followed by instantaneous field processing of strain ranges (12). (The FHWA system for acquiring bridge loading data was originally developed to encourage a national effort to collect bridge strain data. The original system has become obsolete and is no longer operable.) One result is that the records have not been saved for any further processing and information.

CASE BRIDGE MEASUREMENT SYSTEM

Based on reported measurement systems and the present need for additional bridge strain data, the following requirements and aims were proposed for the Case bridge measurement system developed in this project.

Truck Type Information

Annual loadometer survey data give weight information for different truck types. Hence, to correlate truck weight with strain records requires that, for each recorded truck passage, the type of truck be identified. Only a few bridges are located so that nearby weighing stations can be used in conjunction with bridge strain studies. Measurement reports from other states have frequently mentioned that many heavy trucks seem to exit a highway before reaching the weighing stations. Thus, to obtain a good representation of truck vehicles, the measurement system should include a technique for recording truck type, which is automatically processed with the strain data.

Truck Headway and Lane Location

It has been suggested that a significant proportion of damaging loadings are caused by closely spaced trucks simultaneously loading a span. This is recognized in the AASHTO specification for bridge loading that applies to fatigue design (13). It requires all lanes to be simultaneously loaded and, therefore, gives a high load distribution factor for calculating individual girder moments. One aim of this project was to obtain data to develop a model for truck headways and lane location and the frequency of multiple truck crossings on a bridge. In addition, because vehicle velocity may influence headways, this information should also be obtained.

Permanent Records of Processed Data

The easiest way to handle strain records is to process them immediately and convert the records to strain histograms. This is the technique used in the FHWA field measurement system. An objection to this approach is that the records are then no longer available for further processing. One goal of this project was to retain these records for further processing on problems such as bridge dynamics, damping, and load distribution to the stringers. In addition, the nonsinusoidal shape of the actual strain record including its many dynamic oscillations is ignored in current laboratory fatigue testing. These records should be saved because at some future date the exact strain shape record may be found to be significant for fatigue life. For these reasons all recorded data were retained in either digital or analog form.

Fully Automated Data Processing

Because an understanding of bridge loadings is a statistical problem, a large number of truck crossings must be recorded. If any part of the data processing requires that the data be examined manually, the volume that can be processed is severely limited. Therefore, the conclusion was reached that although some manual data acquisition may be acceptable it must be avoided if at all possible in the data processing phase.

Use of Available Instrumentation

Inasmuch as the project had only a 2-year term, it did not involve development and testing of instrumentation. Wherever possible proven equipment was used. A project had been active at Case for several years in which dynamic measurements were made under pile hammers during driving. Both money and time could be saved by using the equipment available from that project wherever possible.

Based on previous field experience it was felt that the project aims could be met in the following manner.

1. Separate the data acquisition on the magnetic tape recorder from the data processing, and do all of the processing in the laboratory and computing center.
2. Use field personnel to manually record information on truck arrival time, headway, and lane information on the tape through generated pulses. Although this required up to a three-man crew it is considerably easier to develop such a system than to try to automate the acquisition of these data. Even a completely automated system would probably need a minimum of two crew members.
3. Store the processed information in digital form on tape. All software programs were written for an available minicomputer.

Work on the project began in August 1971. To avoid inclement weather, we began field testing of the system in September and made strain recordings on a single four-channel tape recorder. In October, the total initial system was tested during 24 hours of continuous recording. The data processing system was developed on an incremental basis. The process of analog-digital conversion proceeded until the available high-speed computer storage was filled. Then the analog tape recorder was stopped until the digital data were processed and printed. The process could thus be continued in small steps. This system was simple enough to be quickly implemented, and the field data were tested. The software for the final processing system, which enabled us to process continuously without having to stop the tape recorder intermittently, was then developed. This system will be described briefly.

By the end of the fair weather season in 1972, six additional bridges had been instrumented and five had been tested. These data were processed during the winter. Further field instrumentation and data acquisition continued in spring 1973, and the data were processed immediately. All field work was completed on the 10 bridges tested in July 1973, and processing was completed in August.

FIELD EQUIPMENT

A schematic of the system is shown in Figure 1. In addition to the strain gauges, two boxes containing a number of buttons that the operators pressed to record truck type and traffic lane are included. In this manner, pulses are generated that interrupt the strain signal for a short period of time. The button boxes are powered and the entire system is managed by a power unit that transmits the signals to the appropriate tape recorder channels. The elements in Figure 1 will be described in detail.

The strain gauges used were standard dual-pattern resistance gauges. They were attached by using contact cement and standard procedures. The Wheatstone bridge was completed at the active gauges by a terminal box containing two inactive gauges. Experience with bridge measurements showed that electronic noise is a serious problem because of the small strain levels encountered. Therefore, the bridge was completed as near as possible to the active gauges, and then shielded cable was used from the gauges to the signal conditioners. By using dual-configuration gauges and hence two active arms in the bridge, the output was doubled.

Separate signal conditioners and amplifiers were used. Both were obtained as government surplus property and thus were not specially selected. The signal conditioners were from Trans-Data, Inc., model BC1031. The differential amplifiers were model 2210 manufactured by Dana. An excitation of 2.5 V was used. An important factor that led to selection of these instruments was that they have very low noise characteristics. Long-time stability is not particularly important because the event measured is so short. In fact, experience showed that, for the continuous bridges tested in Ohio, a considerable apparent zero drift occurred because of temperature effects in the statically indeterminate structure. However, this slow change causes no difficulty inasmuch as stress change due to short-time loads was being measured.

The button boxes and photoelectric cells were constructed by the project (<u>14</u>). Two button boxes were used to record traffic characteristics: one for truck type and one for traffic lane location. Each of these boxes was equipped with 10 buttons. When a button was pressed an electronic pulse of a particular amplitude characteristic of that button was generated. Thus, as many as 10 truck types could be recorded. Likewise, traffic lane location was recorded.

Each of the button boxes was linked to a photoelectric cell. One of these devices was set up at the entrance to the bridge. A light beam was set up on the opposite side of the road focused on the photocell. The passage of a vehicle interrupted the light beam and generated an electronic signal. However, only truck arrivals were noted. The system operated as follows.

When an approaching truck was observed by the button box operator, he pressed the button denoting the type of truck. This was not done until no other vehicles were between the truck and the light beam. Pressing the button set the circuit to be triggered when the light beam was interrupted. This generated the pulse and also lighted a signal indicator on the button box to show that the pulse was triggered. If a button was not pressed, interruption of the light beam was ignored. Thus, not only was the truck type given by the amplitude of the signal, but also by its position the precise arrival time was recorded.

The second button box-photocell system was set up some distance down the traffic stream and performed in the same fashion. The first box was used to record truck type, and the second box recorded lane position. With accurate arrival time data, truck speed and distance headway could be determined.

The button boxes were constructed so that, optionally, they could be used without the photocells. In this mode of operation, the pulse was generated immediately when the button was pressed. Using the button boxes in this fashion was convenient when several trucks arrived at the bridge so closely that the photocells did not have sufficient time to reset themselves. Also, this procedure was used when the volume of automobile traffic was so high that it interfered with the light beam as trucks approached the bridge.

A typical event record is shown in Figure 2. When the pulse was triggered, a square wave pulse went to the recorder. The signal from the strain gauge was interrupted, and a pulse characteristic of the button pressed was generated. After a 20-millisec time lapse, a zero signal, also of 20 millisec, was generated. The pulse amplitude was given by the difference between the two. This avoided problems caused by zero drift of the strain gauge circuit. The strain signal was interrupted for a total of 40 millisec. During this time interval, a truck traveling 60 mph (97 km/h) moved a distance of 3.52 ft (1.13 m).

The power unit was constructed by the project. It provided the power for the button boxes and allowed the strain record to be interrupted and the truck type signals and lane position signals to be placed on the appropriate channels.

The tape recorders used were Hewlett-Packard model 3960, instrumentation magnetic tape recorder. This is a portable unit that can record four channels of FM data at one of three speeds: $^{15}/_{16}$, $3^3/_4$, and 15 in./sec (2.4, 9.5, and 38 cm/s). This instrument performed well but did not have a sufficient number of channels to record the desired number of gauges simultaneously. However, because one of these instruments was available from another project, funds were saved by acquiring only a second one. Because the data were relatively slow, a recording speed of $^{15}/_{16}$ in./sec (2.4 cm/s) was used. Thus, more than 6 hours of continuous recording could be done on an 1,800-ft (550-m) tape reel.

One characteristic of the button box pulse data recorded on the tape unit should be noted. The pulse that was received by the recorder had a very fast rise time and a sharp cutoff. The bandwidth of the recorder was not wide enough to record these square wave pulses. Data in Figure 2 show that the recorded signal overshoots to some degree. However, this signal can still be satisfactorily processed.

DATA PROCESSING

As indicated earlier, one advantage of the data acquisition activity was the ability to

Figure 1. Field equipment system.

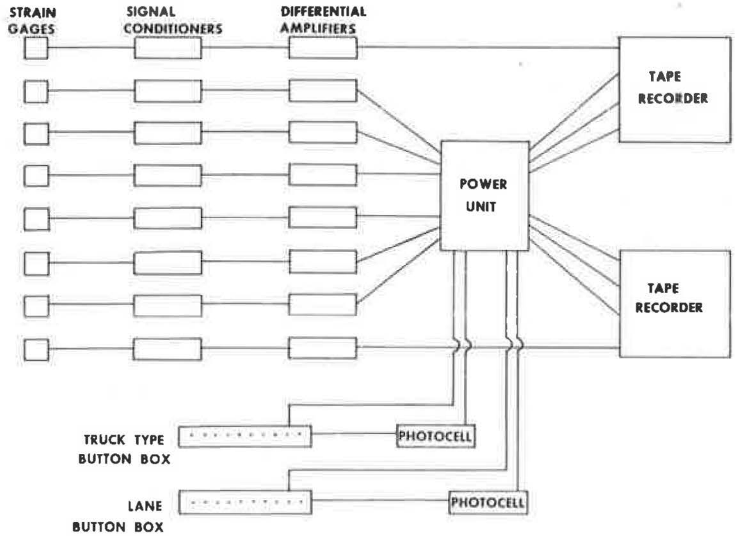


Figure 2. Typical event.

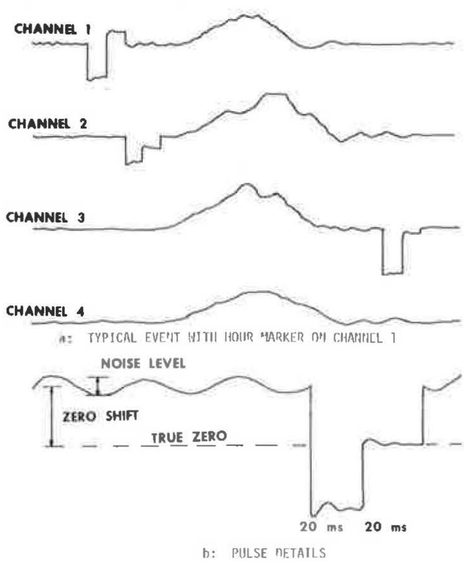
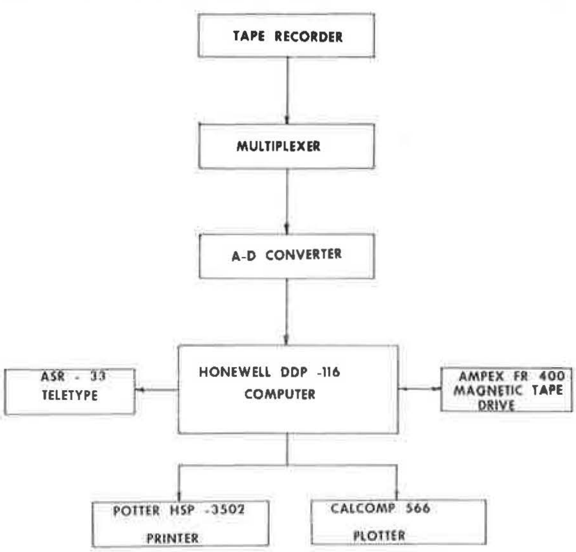


Figure 3. Processing equipment system.



fully automate the data processing. The functions of the system were to convert the analog record into digital form, to sense the arrival of a truck at the bridge (an event), to determine useful data from the button box records, to store the strain records or specific parameters from them, and to transfer the entire event record to magnetic tape. The software for this system was actually developed in an incremental fashion. Only the final system is discussed here.

The processing system is shown in Figure 3. The tape recorder is one of the two tape recorders used to record field measurements. The multiplexer was designed and constructed by the project and can accommodate the four channels of the tape recorder. It condenses four channels of analog data into one channel with a sequence of 2-3-4-1-2-3 and so on. Sampling frequencies of 200, 400, 600, 800, 1,200, and 2,400 samples/sec/channel are available.

The analog-digital (A-D) converter is a Texas Instruments series 834 converter. It receives the single channel of analog data from the multiplexer and converts each sample to digital form.

The computer is a Honeywell DDP-116 computer. It is a solid-state, internally stored program, general-purpose digital computer and is organized as a parallel 16-bit binary machine. The memory cycle time is conservatively rated at 1.7 μsec, and it has a memory capacity of 16,384 words. The instruction repertoire includes 63 commands. Software includes a DDP-116 assembler, debug system, input-output system, diagnostic programs and subroutine library, and FORTRAN IV compiler. The remaining hardware items in the system are commonly available and have obvious functions.

PROCESSING SOFTWARE SYSTEM

A complete and detailed description of the processing software is beyond the scope of this report (14). The processing scheme enables real-time processing of data. This means that while data are being fed into the computer they are being operated on, and the results are simultaneously outputed. Essentially, the entire process depends on the ability of the computer to accomplish all the required operations in the time gap between consecutive inputs of data.

How much time is available between bits of data depends on the sampling frequency of the multiplexer. Two factors that influence the selection of the sampling rate are the tape recorder speed and the form of the data, particularly in regard to the shape of the pulses generated by the various button boxes. As stated previously, data are recorded in the field at a tape speed of $^{15}/_{16}$ in./sec (2.4 cm/s), and the duration of a button box pulse is 20 millisec followed by a zero pulse that is also 20 millisec long (Figure 2). To ensure that processing time was substantially less than recording time, we used the next higher tape speed of $3^3/_4$ in./sec (9.5 cm/s). Because the processing speed is four times faster than the recording speed, the length of a pulse is reduced by a factor of four. The question to be answered now is how many samples are required in a period of 5 millisec so that such a pulse will be identifiable. Because a sample may be chosen along the rising or the descending portions of a pulse or in the region of the peak where there can be much variation in magnitude, at least three samples were necessary for proper identification. Three samples per 5 millisec is equivalent to a sampling frequency of 600 samples/sec/channel. However, because the A-D converter and, hence, the computer, receive data as though they came from one channel, the overall sampling rate is 2,400 samples/sec. At this frequency the time between successive samples if 416 μsec. It is during this time that all required operations must be performed.

It is useful to discuss the general function of the program to give its general capabilities. As indicated above the program must recognize the arrival of a truck. This problem is quite simple because of the truck type-arrival pulse. From this pulse it must identify the truck type and determine its precise arrival time. It must then store the digital record of the strain trace for each of the gauges and identify the lane pulse and hence the lane location and the time of passage of the truck past this point. The program also determines stress range and stores the entire record on digital magnetic tape. The system must also keep a running value for the zeros of all strain gauges. This can be accomplished by maintaining a running average gauge output during times when there is no truck on the bridge. Finally a proper record length must be stored for cases when multiple trucks are present on the bridge at the same time.

The data accumulated during an event are read out to digital magnetic tape. This can include the entire strain record as well as the traffic data. Several bridges were processed in this manner. However, experience showed that a very large volume of digital tape was required to store the results, much more than in its analog form. Therefore, only processed results of current interest were stored, and strain records were not included. The latter data can be most efficiently and inexpensively stored in analog form.

FIELD MEASUREMENTS

The 10 bridges tested in this study were selected to be representative of bridges used by the Ohio Department of Transportation. Since the continuous noncomposite girder is the dominate type in Ohio it, of course, dominated the bridge types tested. Table 1 gives the bridges selected and their characteristics. (All the bridges were steel.) Almost 20,000 truck passages were recorded.

A 24-hour continuous test was conducted on bridge 1 as a preliminary study in October 1971. From the hourly truck traffic volume, the optimum time for testing was determined to be from 8:00 a.m. to 8:00 p.m. As a result five bridges were tested for periods of about 24 hours each spread over 2 days. It was later observed that for the volumes of truck traffic available a total of 12 hours of data would be sufficient for each of the remaining five bridges to give an accurate picture of stress history. This was accomplished by testing between the hours of 10:00 a.m. and 4:00 p.m.

DISCUSSION OF RESULTS

Stress range histograms, truck type distributions, and samples of stress records have been reported elsewhere (14). Only the important results of this study are presented below.

Stress Measurements

Significant stresses in the steel girders (more than 4 ksi or 28 MPa) were found only in the center of end and middle spans of continuous girders and usually on the girders supporting the main traffic lane. The stress ranges adjacent to the piers near the coverplate ends are usually less than 3 ksi (21 MPa). However, these stresses are relatively more significant because they occur in regions where the fatigue sensitivity is greater because of coverplate attachment. High stresses (more than 4 ksi or 28 MPa) were also often found on diaphragms. Such stresses have been reported in other studies and are due to the deformation pattern in the girder-slab structural system. It is not conclusive, however, from the measurements whether diaphragms should be increased or decreased in size or number.

It appears from the stress measurements that the stresses due to random truck traffic are significantly below the fatigue design allowable stresses. Because fatigue-causing loading was the main purpose of the field study it was observed that the margin of safety against fatigue in all the bridges studied is quite large. This conclusion, of course, presumes that the truck weights and volumes now being carried will remain constant over the life of the bridge. In fact, field studies such as this one, which may be used to justify the safety of raising legal allowable loads, may in time lead to premature fatigue damage.

Although allowable design stress margins appear adequate when compared with measured values, the field results did show higher stresses than were observed in several other states (3 through 11). This is probably an indication of the industrial nature of the state of Ohio and the type of materials transported over the roads such as steel and machine products.

Truck Headway Data

This field project was perhaps the first in the United States to record precise headways and frequencies of multiple truck crossings in conjunction with bridge strain measurements. These headway data can be used independently as empirical information for a model of truck spacings and hence truck loadings. It indicates that for fatigue design the assumption that all lanes are simultaneously loaded is overly conservative. The most commonly proposed spacing model is based on the Poisson distribution and is often used in relation to automobile spacings. It gives probability of the time between successive trucks along a roadway as

$$F(t) = 1 - e^{-ut} \approx ut$$

for small headways where

$F(t)$ = probability that the time between successive trucks is less than t and
u = truck volume in vehicles per unit time.

Dividing headway into discrete time intervals gives

$$F(t_2) - F(t_1) = u(t_2 - t_1)$$

The headways given in Table 2 are divided into 0.2-sec intervals; for the Poisson model to be accurate the values should be constant (at $u \times 0.2$ percent) in the small (<3 sec) headway range. The number of occurrences predicted for the short time intervals by the Poisson model is also given in the table. In most cases the values in Table 2 given by the Poisson model are higher than the measured value, indicating that the model is a conservative prediction as far as truck loading superpositions are concerned. The model is not accurate in the small headway values because it implicitly assumes that as a truck gets close to a preceding truck it moves to the passing lane as if the first truck is not even present. This assumption ignores driver behavior and reaction times and thus is not accurate in short headways.

For headways greater than 1 sec the agreement between model and observation is quite reasonable. For example, for bridge 3, u = 70 trucks per hour, and Table 2 shows 1.5 percent of observed headways less than 1 sec. The Poisson equation predicts $(70/3{,}600) \times 1$ or 1.9 percent should have headways less than 1 sec. Similar good agreement can be seen in the other bridges except for bridge 10, which only had 1 lane in each direction and thus clearly inhibited trucks from getting close and attempting to pass. It is clear then from both the Poisson model and the results in Table 2 that for commonly encountered truck volumes the frequency of more than one truck on the bridge at a time is small. This suggests that current bridge loadings need to be revised as far as fatigue is concerned.

Impact

The magnitude of impact due to bridge and truck dynamics can only be measured by comparing stresses of identical vehicles in a crawl and at a normal speed. This was not done in this study. However, studying the stress records may give some indication of the impact by looking at the magnitude of dynamic oscillations. In general, the im-

Table 1. Description of bridges.

Bridge	Location	Type[a]	Lanes	Girder No.	Girder Spacing	Span Length	Route Type	Truck Passages
1	Cuy271-721	BC	3	8	7'4"	41'-66'-41'	Urban Interstate	3,771
2	Cuy71-384	BC	2	5	9'6"	37'3"-46'-37'3"	Suburban Interstate	1,995
3	Cuy71-100	BC	2	6	7'11"	44'-63'-44'	Suburban Interstate	1,507
4	Lak90-526	BC	2	8	7'4½"	64'-80'-64'	Suburban Interstate	1,268
5	Ric71-1068	GC	2	6	7'11"	68'-114'-114'-68'	Rural Interstate	1,267
6	Atb90-1450	BC	2	6	7'11"	48'7¼"-81'-48'7¼"	Rural Interstate	1,624
7	Por80S-130	BC	2	6	7'11"	48'-60'-60'-48'	Suburban Interstate	1,703
8	Cuy90-2181	BSi	4	Varies		75'	Urban Interstate	2,958
9	Sum21-778	BC	2	5	7'6"	36'-45'-36'	Non-Interstate, divided	1,053
10	Por14-1131	BC	2	5	7'4"	48'-60'-48'	Undivided	1,733

Note: 1 ft = 0.3 m; 1 in. = 2.5 cm.

[a]B = rolled beam, G = welded plate girder, C = continuous, and Si = simple span.

Table 2. Truck headway occurrences.

Headway (sec)	Bridge 1	2	3	4	5	6	7	8	9	10[a] A	10[a] B
0.00 to 0.20	4	10	5	0	2	1	0	19	2	0	0
0.21 to 0.40	16	3	4	0	1	3	0	14	3	0	0
0.41 to 0.60	23	15	5	1	2	4	9	15	5	0	0
0.61 to 0.80	33	9	3	4	5	9	7	42	3	0	1
0.81 to 1.00	30	14	5	3	2	3	7	41	4	0	0
1.01 to 1.20	28	20	14	5	3	7	12	54	9	0	0
1.21 to 1.40	49	17	8	6	14	4	23	56	8	1	0
1.41 to 1.60	45	19	7	4	9	11	36	46	5	1	1
1.61 to 1.80	49	30	10	3	10	13	20	63	15	3	6
1.81 to 2.00	51	21	8	6	14	9	11	65	7	6	3
2.01 to 2.20	38	11	3	6	14	14	7	50	21	7	5
2.21 to 2.40	44	12	8	2	11	10	16	48	5	5	5
2.41 to 2.60	51	10	12	2	18	8	17		8	10	6
2.61 to 2.80	34	10	10	4	15	8	10		5	14	2
2.81 to 3.00				4	16	11				18	3
3.01 to 3.20				6	15	7					
3.21 to 3.40	3,276	1,794	1,405	6			1,528	2,445	970	902	734
3.41 to 3.60				2	1,116	1,502					
>3.60				1,204							
Total	3,771	1,995	1,507	1,268	1,267	1,624	1,703	2,958	1,053	967	766
Predicted occurrences	36	10.5	6	4	7.4	6.3	13	42	5.3		
Hourly truck volume	170	95	70	60	105	70	140	250	90	150	
Percentage in passing lane	53	5.1	3.7	2.1	3.4	3.6	5.1	59	3.0		

[a]Dual-direction bridge.

Table 3. Measured girder distribution factors.

Bridge[a]	Girder Spacings	α	Bridge[a]	Girder Spacings	α
1	7'4"	15	7	7'11"	12.5
2	9'6"	14.6	9	7'6"	13.6
3	7'11"	15	10	7'4"	16.3
4	7'4½"	13.5			
5	7'11"	17.8	Average		14.7
6	7'11"	14.5	Code value		5.5

Note: 1 ft = 0.3 m; 1 in. = 2.5 cm.

[a]Bridge 8 had variable girder spacings.

pact oscillation is less than 15 percent of the peak stress range and is thus somewhat less than the AASHTO code value (13). However, for fatigue damage both the impact oscillation, which increases the maximum stress, and the residual vibration after truck passage, which reduces the minimum stress, must be considered. This is because fatigue life of highway bridges is now thought to be controlled strictly by stress range magnitude, which is the difference between maximum and minimum stress (15).

Girder Distribution Factors

By locating gauges on parallel girders in a span in this study it was possible to estimate the distribution of total truck bending moment to the individual girders. The girder distribution factor is

$$M_g = M_{WL} \frac{S}{\alpha}$$

where

M_g = moment range on critical girder,
M_{WL} = moment range on total bridge cross section due to wheel load,
S = girder spacing, and
α = measured constant.

A summary of values from bridges tested is given in Table 3. The average percentage of total wheel load moment distributed to the most critical girder is S/14.7 compared with the AASHTO code value of S/5.5. Measured girder distribution values are slightly below the generally reported S/12.5 to S/13.5 because we used stress range rather than maximum stress to determine the distribution. Based on these field measurement studies, for fatigue loading of multilane slab-girder bridges, one-half the usual distribution factor to the girder should be used—that is, a value of S/11, where S is the spacing in feet (meters) between girders. Although this value may be modified by further analysis it is clear that the assumption that parallel lanes be fully loaded is conservative as far as repetitive fatigue load is concerned.

Truck Weighing

Some bridge measurements made in conjunction with a weighing station showed the feasibility of using the bridge itself as a load scale for directly weighing trucks as they cross the bridge. This would enable a large number of vehicles to be weighed economically and to avoid the known problem of trucks exiting and bypassing open weighing stations. Information should automatically be obtained on gross truck weight, axle length, and perhaps axle load distribution. An example of such correlation of gross weights with stress range measurement is shown in Figure 4. The strain shown is the sum of stress ranges on the six parallel girders, and the vehicles in the figure are tractor trailers with wheel bases of 30 to 31 ft (9.1 to 9.4 m). In most cases where section modulus is difficult to estimate, calibration by weighing known trucks is necessary.

Measured and Predicted Stresses

Table 4 gives predicted versus measured average stress range and standard deviation of stress range at four girder locations on the same bridge (bridge 2, 14). The predicted values were obtained by combining a truck weight histogram with a bending

Figure 4. Stress range (from six gauges) versus truck weight.

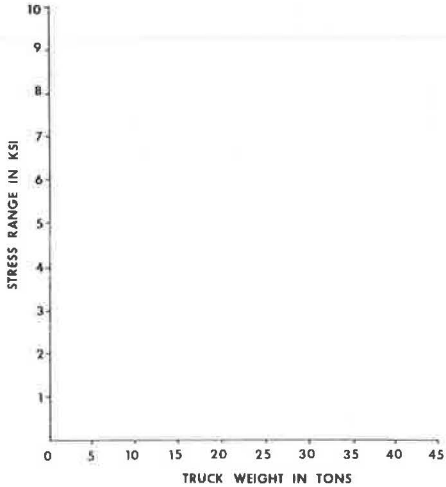


Table 4. Predicted and measured stress ranges.

	Average Stress (psi)		Standard Deviation (psi)	
Location	Predicted	Measured	Predicted	Measured
Middle of end span	1,439	1,385	711	626
End of cover plate in end span	1,119	908	558	336
End of cover plate in center span	941	954	462	613
Middle of center span	1,356	1,438	624	550

Note: 1 psi = 6.9 kPa.

Table 5. Predicted and measured average stress ranges of multiple crossings.

	Stress Range (psi)	
Location	Predicted	Measured
Middle of end span	1,704	1,683
End of cover plate in end span	1,337	1,153
End of cover plate in center span	1,021	1,142
Middle of center span	1,738	1,766

Note: 1 psi = 6.9 kPa.

moment influence line at each girder location. The truck weight histogram was compiled from the combined Ohio loadometer survey inasmuch as a weighing station was not available at the bridge site. The truck type distribution, however, used to combine various vehicle types was recorded at the site as explained above. Despite the fact that there are obvious weight differences expected between the trucks from the loadometer survey and the trucks at the site, the agreement between measured and predicted stress ranges was generally quite good. Table 5 gives stress comparisons for the influence of short headways on truck loading superposition. The predicted or calculated values were based on the Poisson model for headway spacings rather than the observed headway spacing in Table 2. The results given in Tables 4 and 5 are typical of the 10 bridges studied and indicate the possibility of accurately estimating truck loading effects on girder sections.

Fatigue Design

A major conclusion of the field measurements reported to date is that there is a clear need to separate fatigue loading from yielding or ultimate design load. Fatigue represents an averaging process in which hundreds of thousands and perhaps millions of cycles of load are needed for failure to occur. Thus, it is illogical to use an extremely rare design truck loading that is expected to occur only a few times during the life of the structure. Truck properties are volume, girder load distributions, impact factors, and the assumption of trucks in more than one lane should be based on average conditions. Safety can then be specified in a uniform, consistent manner from site to site with both load and resistance safety factors (16, 17).

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