Portable Recorder for Bridge Stresses

Mark W. Williams, Norton and Schmidt Consulting Engineers, Kansas City, Missouri
James W. Baldwin, Jr., Department of Civil Engineering, University of Missouri—Columbia

Development and operation of a portable instrument for recording strain events in bridges under field-service conditions are described. The instrument consists of a transducer, which is clamped to the flange of a bridge by four allen screws; a set of mechanical counters driven by electronic logic circuitry; a battery pack; and a tamper-proof enclosure. As much as 80 d of continuous operation can be realized before batteries must be serviced. Each counter is incremented every time the strain reaches the triggering level selected for that counter. Triggering levels are selected to be distributed over a range slightly greater than the strain range expected in the bridge. For the usual case, in which the triggering levels are all in the elastic range, a simple hand calculation will produce a stress histogram from the counter readings. The theory and a procedure for predicting bridge life from the collected data are also presented. Results of a short field test indicate that the instrument provides a practical and economical means by which relatively unskilled personnel can collect stress-history data.

In recent years, limited field studies (1, 2, 3, 4, 5, 6, 7, 8, 9, 10) have indicated that actual service stresses in highway bridges may be far below the calculated maximum stresses for which bridges are designed; many more data are needed, however, before conclusions can be drawn as to whether present design criteria can or should be revised.

Field studies of service stresses now require a substantial amount of expensive equipment and skilled research personnel. Unfortunately, these studies have been limited, by expense, to observations of a relatively small number of bridges for relatively short periods of time. Clearly, there is a need for a more economical means of data collection that will allow studies to be performed on a much wider variety of bridges for much longer periods of time.

Availability of the instrument described in this paper will make it possible for highway department personnel to collect and interpret, on the spot, load-history information from a variety of bridges at a relatively low cost. In addition to determining the actual service stresses in bridges, the instrument could also be used to observe (a) the long-range trends of traffic volume, (b) the effectiveness of weigh stations, (c) the effects of changes in legal weight limits, and (d) the presence of overweight vehicles in areas where there are no weigh stations or at times when such stations are closed.

THEORY OF OPERATION

Fatigue Considerations

Most recent load-history studies have incorporated a fatigue analysis based on collected data, which requires knowledge about the behavior of the particular material under fatigue loading and the important parameters that govern this behavior. Fisher and others (13) conducted in-depth studies on fatigue with respect to weldments on steel beams and concluded that stress range alone is the dominant variable in fatigue analyses of structural steel bridges. Fatigue curves for a variety of structural details have been developed from the accumulated data. These curves are represented by a linear log-log relation between the stress range (Sr) and the cycles to failure (N). The stress range, as defined by Fisher and others (13), Douglas (5), and Munse and Stallmeyer (12), is taken as the algebraic difference between the maximum and minimum stress values from each loading cycle. A typical stress or strain trace is shown in Figure 1.

Construction of Histogram

Load histories are generally collected as an analog recording that is subsequently processed through an analog-to-digital converter. Then the maximum and minimum stress values are determined from the digital record and are combined to obtain the stress range. The data are subsequently grouped in discrete intervals from which the frequency of occurrence of stress ranges within each interval may be determined. The result of this procedure, represented graphically, is known as the stress-range-frequency histogram (5). Figure 2 shows an example of such a histogram.

Assume that a series of counters is introduced in place of the sophisticated system of data acquisition. Each counter is incremented when the stress level reaches a preselected value, as shown in Figure 3. A given counter cannot be incremented again until the stress level has gone below some preselected value near zero. For the single cycle shown, counters 1 to 4 are each incremented once. Counters 5 and 6 are not incremented because the analog signal representing the strain trace does not exceed their corresponding stress level.

If it is assumed that a similar sequence of counting occurs for each trace caused by a passing vehicle, then, for the length of the test period associated with a particular bridge study, each counter total (C_i) reflects the number of times that its associated stress level (σ_i) was exceeded. Furthermore, if no negative portion of the strain trace exists, as in Figure 3, then the maximum value of σ in any trace is also the stress range for that trace. If Sr_i is defined as the stress range equal to σ_i and Cr_i is the number of times Sr_i has been exceeded, then

$$Cr_i = C_i \qquad i = 1, 2, \ldots, m \tag{1}$$

where m is the number of active counters. If the highest triggering level (σ_m) is high enough that it is never exceeded,

$$Cr_m = C_m = 0 \tag{2}$$

and Cr_{m-1} is the number of occurrences of stress ranges between the values of Sr_{m-1} and Sr_m. In general, $Cr_i - Cr_{i-1}$ is the number of occurrences of stress ranges between the values of Sr_{i-1} and Sr_i. The stress-range histogram can thus be constructed directly from counter differences. Clearly, C_1 is equal to the total number of significant events that occurred over the test period.

Consider now that a negative portion of the strain trace does occur, which it would in a multispan bridge structure. Figure 4 shows a simulation of a typical loading cycle in which each counter associated with a negative stress level is incremented in the manner previously indicated for positive counters. The stress levels (Figure 4) must then be combined by some method in order to obtain the necessary stress ranges for subsequent analyses.

The stress range for the trace shown in Figure 4 just exceeds σ_3 to σ_5. In general, it can be assumed that stress events that produce relatively large positive peaks also produce relatively large negative peaks. Then the stress levels shown in Figure 4 may be associated to form stress ranges by a comparative analysis of the cumulative number of exceedences (C_i) and (C_j) of positive and negative stress levels (σ_i) and (σ_j) respectively.

Figure 1. Typical stress or strain trace.

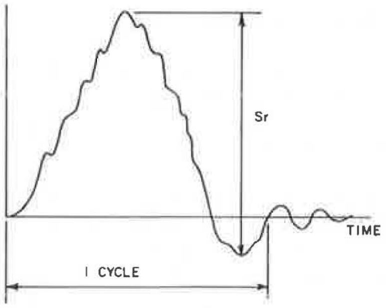
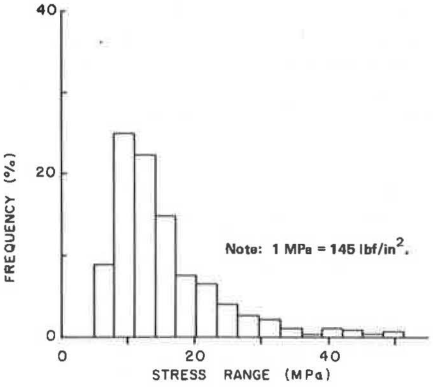


Figure 2. Stress-range histogram.



Note: 1 MPa = 145 lbf/in^2.

Figure 3. Simulated strain trace and associated counting levels.

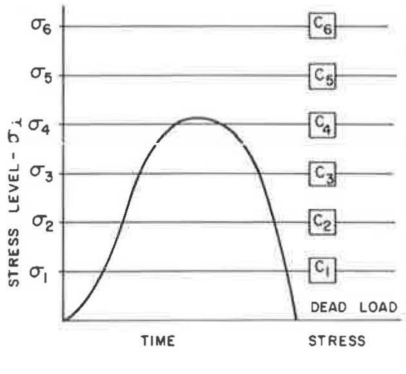
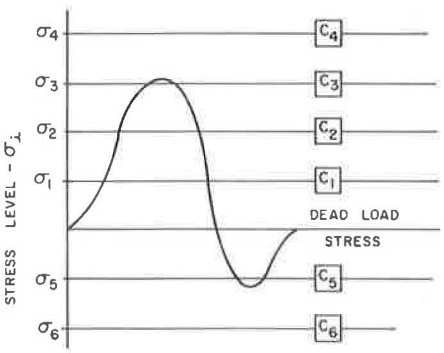


Figure 4. Simulated strain trace for actual loading cycle.



This procedure is initiated at the extreme positive and negative stress levels (in this case σ_5 and σ_8). By a process of elimination, the cumulative number of exceedences for each possible stress range is determined. The following example, which uses the stress levels and cumulative counter totals shown in Figure 5, illustrates the procedure.

First, the extreme counter totals (C_5) and (C_8) are compared. Because both C_5 and C_8 are zero, it is clear that there were no stress ranges in excess of σ_5 to σ_8. Next, counter totals C_4 and C_7 are compared. The lower total (C_4) is equal to the cumulative number of exceedences (Cr_6) of stress range (Sr_6) where Sr_6 is equal to the algebraic difference of σ_4 and σ_7. The higher value, in this case C_7, is retained and compared to the next descending counter (C_3). Because C_3 is less than C_6, $C_3 = Cr_5$ where Sr_5 is equal to the algebraic difference of σ_3 and σ_7. This procedure is continued until all counter totals have been considered.

Note that if C_3 had been equal to C_7 then $Cr_5 = C_3 = C_7$. In this case, no counter total is retained and the next comparison is made between C_2 and C_6. This procedure is followed whenever two counter totals are compared and found to be equal.

The final stress ranges and the cumulative number of exceedences for each range are also shown in Figure 5. The stress-range histogram for the data in Figure 5 is shown in Figure 6.

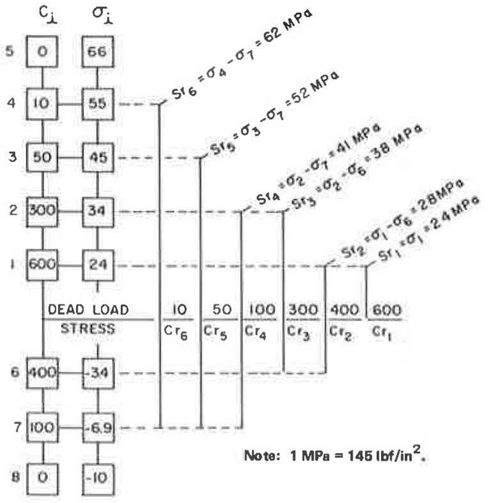
Cumulative Damage in Fatigue

In addition to determining the stress-range histogram, it may be desirable to estimate the long-range effects that fatigue has on the usable life of a bridge. Miner's cumulative damage theory (11) is commonly used as a basis for fatigue analysis and is used here, for simplicity, to show how data similar to those shown in Figure 6 may be used to determine the fatigue damage to a bridge caused by the random loading cycles encountered under service conditions. Damage is defined as the fractional part of the total life of the structure expended during any given number of cycles.

According to Miner's theory, the total damage is independent of the order of application of random loading cycles. Based on this assumption, the total damage is given by

$$\text{Damage} = \Sigma\ (n_\ell/N_\ell) \leqslant 1.0\ \text{(failure)} \qquad (3)$$

Figure 5. Determination of stress ranges.



Note: 1 MPa = 145 lbf/in^2.

where n_ℓ is equal to the actual number of cycles at stress range (Sr_ℓ) and N_ℓ is equal to the number of cycles to failure at Sr_ℓ.

The number of cycles to failure (N) should be determined from a fatigue curve that is based on experimental data from structural details that are the same as, or similar to, the actual detail or details under consideration. A fatigue curve developed by Fisher and others for beams with end-welded cover plates (13) is shown in Figure 7.

Figure 6. Stress-range histogram and cumulative exceedence curve.

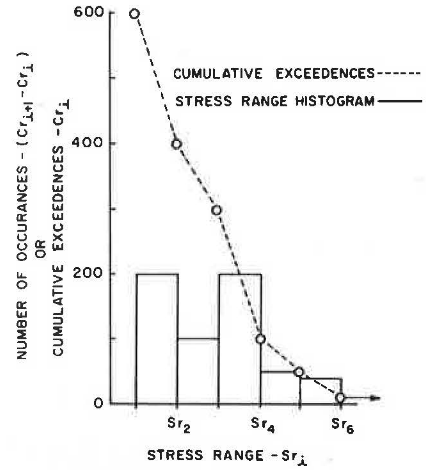


Figure 7. Fatigue curve for beams with end-welded cover plates.

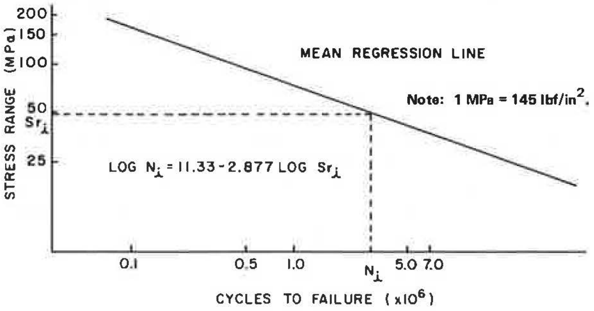
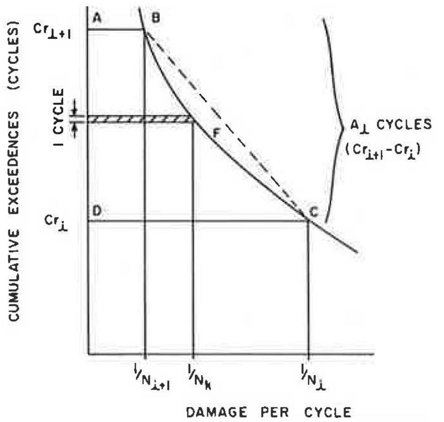


Figure 8. Cumulative fatigue damage.



Assume that n stress cycles with varying amplitudes (Sr) are applied to a bridge and that these cycles are then arranged in descending order of amplitude and plotted as shown in Figure 8, with the cycle number as ordinate and 1/N as abscissa. Damage done by the Kth cycle is equal to $1 \times (1/N_k)$, or the cross-hatched area shown in the figure. Thus the total damage done by the n cycles is

$$\text{Damage} = \sum_{i=1}^{n} 1 \times (1/N_i) \qquad (4)$$

which is clearly the total area under the curve. Furthermore, for any cycle (K), K - 1 is the number of cycles with amplitudes exceeding Sr_k. Thus, the curve shown in Figure 8 is also the cumulative exceedence curve, which can be closely approximated by plotting Cr_i versus $1/Nr_i$ as the number of cycles causing failure at a stress range of Sr_i. A sample damage curve is shown in Figure 9. The total damage may also be calculated numerically; such a calculation is given in the following table (1 MPa = 145 lbf/in^2):

Stress Range (MPa)	Exceedences	Damage	
		Per Cycle (1/N x 10^8)	Total
76	0	105	
			[(105 + 58.8)/2] (10 - 0) = 819 x 10^{-8}
62	10	58.8	
			[(58.8 + 42)/2] (50 - 10) = 2016 x 10^{-8}
52	50	42	
			[(42 + 25.2)/2] (100 - 50) = 1680 x 10^{-8}
41	100	25.2	
			[(25.2 + 11.5)/2] (300 - 100) = 3670 x 10^{-8}
38	300	11.5	
			[(11.5 + 6.8)/2] (400 - 300) = 915 x 10^{-8}
28	400	6.8	
			[(6.8 + 3.4)/2] (600 - 400) = 1020 x 10^{-8}
24	600	3.4	

This procedure results in a figure for expended bridge life of 0.0101 percent.

INSTRUMENT DESIGN

Strain Transducer

The strain transducer is a sensing device used to produce an analog voltage signal proportional to the strain in a structural steel bridge girder. The sensing element used in this study is a Hewlett-Packard model 24DCDT-100, a direct-current differential transformer (DCDT) that requires 24-V excitation and provides an output signal of ±10 V over a displacement range of 0.24 cm (±0.1 in). The actual strain is therefore the displacement divided by the gauge length. The gauge length of the prototype transducer is 102 cm (40 in), which provides

Figure 9. Sample damage curve.

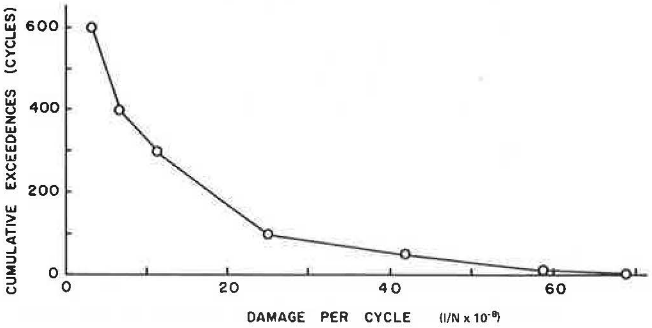


Figure 10. Prototype strain transducer.

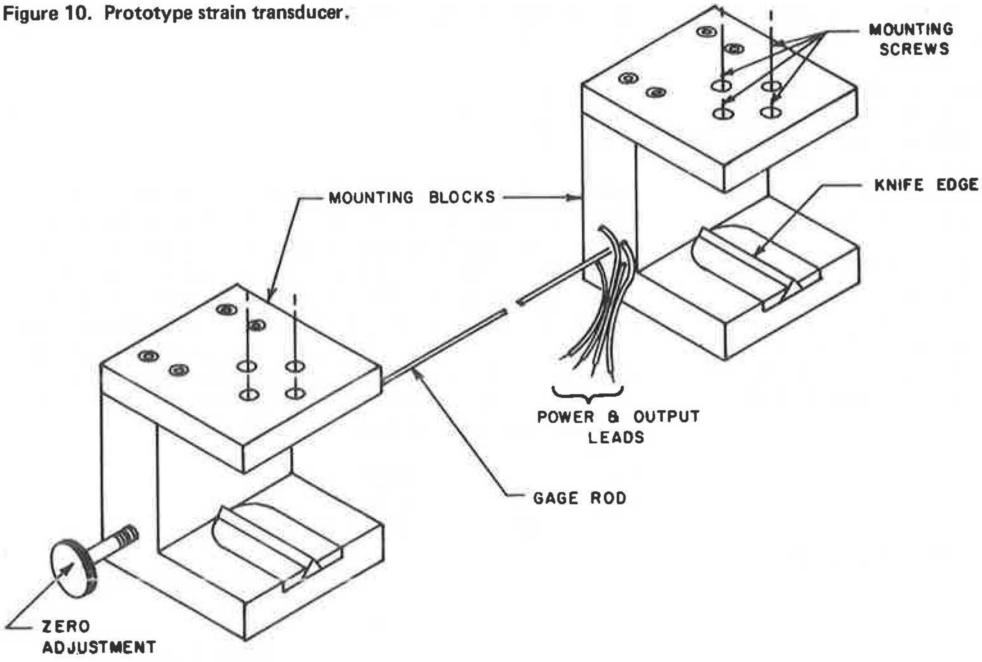
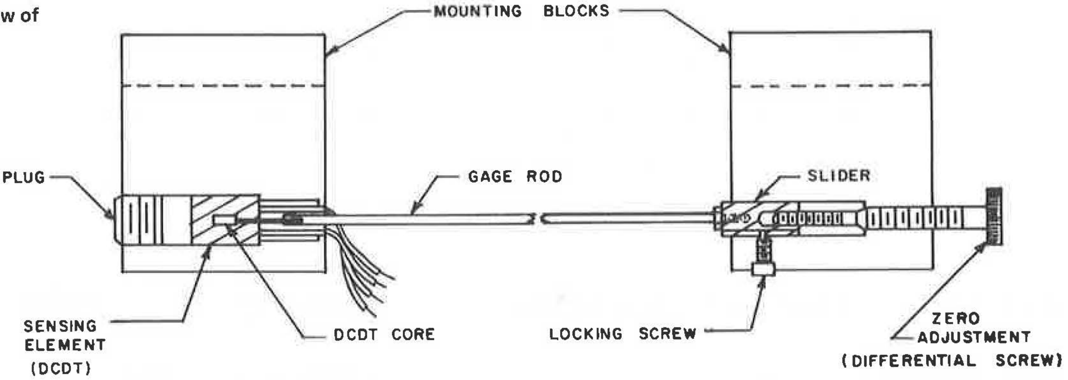


Figure 11. Cross-sectional view of prototype transducer.



an output signal of approximately 4 mV/microstrain without amplification. The prototype transducer is shown in Figure 10; the DCDT is located internally in the mounting block on the right of the figure. A sectional view of the transducer and other internal parts is shown in Figure 11.

When the transducer is attached to a bridge girder, the gauge rod is supported at its midpoint by a teflon bearing mounted on a steel angle that clamps onto the bottom flange of the girder. This support minimizes vibration of the rod caused by wind and other dynamic loads and helps to conform the rod to the curvature of the girder.

A relatively small modification to the recorder would permit the use of an electric-resistance strain gauge as a transducer, greatly reducing the gauge length over which the strain is measured and cutting the power requirements in half. But one objective of this particular design was to produce a fairly rugged, reusable transducer that could be installed in the field without special tools or skill.

Recorder

The recorder is an electronic package designed to receive and monitor the output signal from the strain transducer. Inside the recorder, a series of ten counters, each triggered at a separately adjustable stress or strain level, record stress events as they occur. All counters are rearmed simultaneously when the input signal crosses the zero line. The recorder contains circuitry for filtering out base-line drift caused by temperature and other relatively long-term effects.

Power Supply

The instrument may be powered by any direct-current (dc) power source that satisfies the following requirements: 24-V system voltage (nominal); 38-mA strain transducer; 6-mA recorder. Because both the output of the strain transducer and the triggering voltages are directly proportional to the power-supply voltage, the instrument will function normally under dc power-supply fluctuations from 28 to 20 V.

The system has been tested with a power supply consisting of two 12-V automobile batteries rated at 342 kC (95 A·h). At 21°C (70°F) this battery pack will supply enough power for instrument operation up to approximately 80 d between recharges. Although this is an economical power supply that provides for long periods of operation, the size of the batteries requires a separate battery case. The 25-kg (55-lb) weight of each of these batteries also makes them rather difficult to handle in the field.

A pair of 12-V rechargeable dry cells intended for portable television sets has also been used to power the instrument. These batteries are much lighter and smaller and will fit inside the recorder cover. At 21°C (70°F) two of these batteries will power the unit for about 2 weeks between recharges. Commercial literature indicates that they can be recharged 30 or 40 times.

Total Instrument Package

The transducer, the recorder, and the power supply (except in the case where automobile batteries are used) all fit inside a tamper-proof 122 × 122 × 23-cm (48 × 48 × 9-in) enclosure. Both the transducer and the tamper-proof enclosure are clamped to the bottom flange of the steel girder with screws located inside the enclosure. No special preparation is required for the transducer.

Basic resolution of the electronic countercircuits is ±10 mV [0.52 MPa (75 $\mathrm{lbf/in^2}$) of stress for steel], and the resolution is theoretically infinite. The calibration factor for the differential transformer varies 4 or 5 percent between transformers. The precision of the instrument is therefore dependent on the effort put into matching the recorder circuit to the transducer. However, a 1 or 2 percent match is not difficult.

Although a precise definition of the overall accuracy of the instrument would be quite complex, it is reasonable to assume that, for the majority of data collected on steel bridges, actual triggering levels will be within ±1.03 MPa (150 $\mathrm{lbf/in^2}$) of the value set.

SUMMARY AND CONCLUSIONS

The self-monitoring instrument for load-history studies is presented here as an economical means for collecting data that reflect the actual service stresses occurring in a structural steel highway bridge. The availability of the instrument will make possible the collection of load-history data from a wider variety of bridges for much longer periods of time than may be obtained by using present techniques.

The complete system consists of (a) the strain transducer, (b) the recorder, and (c) the battery pack. System design is such that the instrumentation may be attached to a structural steel bridge girder and left in place for extended periods of time subject only to battery recharging at intervals of approximately 14 to 80 d, depending on the battery pack used. Simplified data-analysis techniques allow accumulated data to be used directly or in terms of bridge fatigue life. Installation of the instrument requires approximately 20 min, and batteries can be replaced and a set of readings taken in about 5 min. Field tests show that the instrument works well under field conditions.

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