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SHM OF BRIDGES USING WEIGH-IN-MOTION

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Abstract

Fatigue analysis is an important consideration for evaluating the health of the bridges. To develop a fatigue analysis, load and resistance are two essential concerns. In fact, load due to traffic vehicle differs considerably from the designed load. To estimate the remaining fatigue life more accurately, a refined evaluation load procedure is desirable. In this paper, we propose a new method to incorporate Weigh-in-Motion (WIM) technology into Structure Health Monitoring (SHM) data analysis to understand the performance of the bridges and establish fatigue life of the girders and the decks. The method chooses several corresponding strain peaks to calculate vehicle parameters, such as truck speed, axle spacing, axle weights, and gross weight. The calculated truck parameters are used as input for a program of Semi-continuum method of analysis for bridges (SECAN) to check the calculated result and to study the performance of bridges. This allows utilization of the output of SECAN for input in the fatigue analysis to estimate the fatigue life.

INTRODUCTION

A recent bridge collapse in which five people perished reminded the public of the deteriorating health of the infrastructure in Canada [1]. The evaluation of the safety of the bridges can be achieved through Structural Health Monitoring (SHM). The challenge is how to evaluate and utilize the data to assess structural health. We aim at incorporating Weigh-in-Motion (WIM) technology into SHM data analysis to understand the performance of the bridges and establish fatigue life of the girders, girder-diaphragm connections and the decks.

Bridge structures experience millions of repeated cyclic loads due to vehicle weights, which can lead to fatigue failure and structure deficiencies [2]. As a result, fatigue analysis becomes an important consideration from two perspectives: to determine when and where fatigue cracking happens and to make budget for rehabilitation and replacement. To develop a fatigue analysis, two essential concerns are needed: load and resistance [3]. Load and resistance vary significantly in time. The actual live loads due to vehicle weight might increase and differ from the designed load. In contrast, resistance can decrease due to degradation of material and human errors in design and construction. Therefore, the useful service life of the bridge could be considerably reduced. To accurately estimate a fatigue life, it is necessary to incorporate truck traffic characteristics, such as truck speed, truck configuration and truck axle weights, into the fatigue analysis.

In this paper, we propose a method to utilize SHM data for input and WIM as a method to calculate truck speed, truck configuration and truck weight going over the bridge. Also, we use the program of Semi-continuum method of analysis for bridges (SECAN) to study the response of the bridge. This will allow us to estimate the fatigue life of in-service bridge.

PROPOSED SYSTEM AND METHODOLOGY

Proposed system

In the past WIM and SHM were separate systems and had their own objectives. This paper integrates WIM and SHM by using common *civionics* system, into an efficient and effective method to evaluate live load for fatigue analysis. Current fatigue load models focus on single fatigue vehicles that simplify the bridge load spectra. In fact, load differs considerably and might be much higher than the assumption in the design procedure [4]. To estimate the fatigue life more accurately, a refined evaluation load procedure is desirable.

From a practical point of view, our *civionics* system is to incorporate WIM method into SHM data analysis to service the bridge management (Figure 1). The *civionics* integrated system can be divided into four main steps: 1) Sensor system and Data acquisition to collect the raw data from the field; 2) Data analysis to utilize WIM method to evaluate the model parameters, such as truck speed, truck configuration and truck axle loads; 3) Model analysis to simulate the performance of the bridge; 4) Fatigue analysis to estimate the remaining fatigue life of the structure under consideration; 5) Decision making to send the result to the manager to plan budget for rehabilitation or replacement.

Methodology

The methodologies for the steps Sensor System and Data Acquisition are discussed in the literature [5]. This paper mainly describes the methods in the steps: Data Analysis, Model Analysis and Fatigue Analysis.

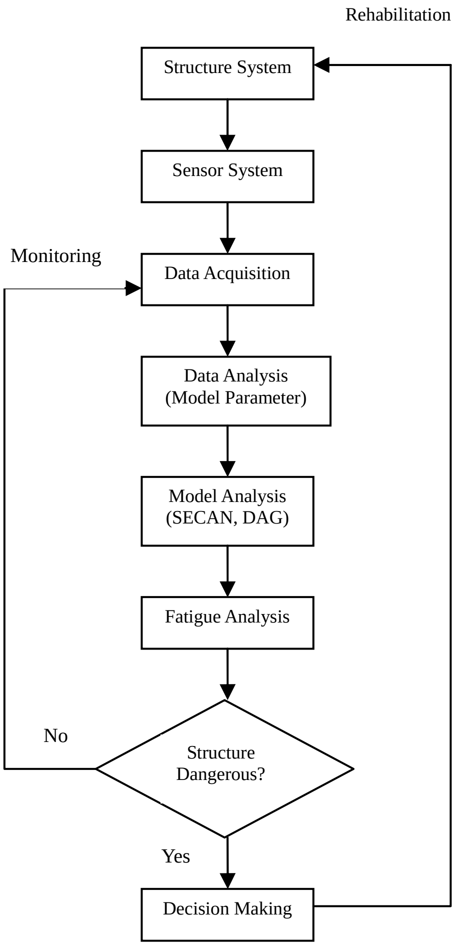

Figure 1 The flowchart for the integrated system

Method in Data Analysis

In this step, we analyze the raw data from the data acquisition system to get the truck parameters, such as truck speed, truck configuration and truck load. The raw data is first of all smoothened out by using a moving average program to take care of the high fluctuations in the strain readings due to the dynamic effects and vibration of the deck.

1) Determination of Speed

The speed of the vehicle is determined by using corresponding time tags of peaks for girder strains at different sections where strain gauges are mounted. The speed of a vehicle is calculated by using the raw data. Suppose there are two strain gauges mounted on Section A-A and B-B, shown as Figure 2.

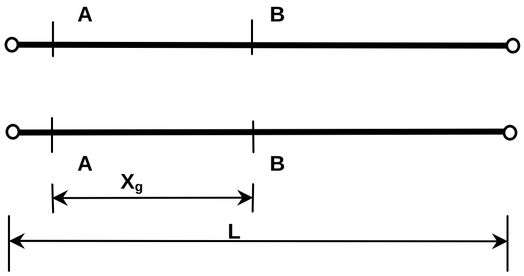

Figure 2 Strain gauges mounted at Section A-A and B-B

The speed can be calculated with the known values of the sampling rate in samples per second, SR, the distance between two sections, X_g, and the time tags of peak strains at sections A-A and B-B, designated as $TT_{peak\ A}$ and $TT_{peak\ B}$. The following formulas can be used to calculate the time interval between the two peaks (t) and the truck speed in km/hr (V).

$$t = (TT_{peak\ B} - TT_{peak\ A}) / SR \qquad (1)$$

$$V = 3.6\ X_g / t \qquad (2)$$

Determination of Axle Spacing

It is assumed that the vehicle is moving at constant speed and along a straight lane. The axle spacing is determined by using the speed of the vehicle and the time difference between successive peaks of the same strain-time plot. In the processing of the field data, possibly because of the relatively small sampling rate, the two closely spaced axles of the truck appear as one load. So, the computed axle distance corresponds to the centre of the tandems.

When the truck moves through the bridge, each axle or dual-axle tandems will create the peaks of the stress in the girder, which are monitored by the strain gauges. The truck axle spacing can be evaluated by the strain peaks. Figure 3 shows strains due to a truck with four axle groups.

The method to calculate the axle spacing is as follows: 1) Identify peak strains in the gauges near the support of the girders and designate these as peak1, peak2, peak3 and peak4; 2) Use equation (1) to estimate the time intervals between successive peaks, designated as t_1, t_2 and t_3; 3) Utilize the formula given below to calculate the axle spacing, X_1, X_2 and X_3.

$$X_i = t_i * V / 3.6 \qquad (3)$$

Where, Xi = Distance between successive axle groups in meters and
t_i = Time interval between corresponding strain peaks in seconds

It is not easy to pick up strains due to peak1, as it only signifies a perturbation in strain due the speed of the truck. Hence it may not be possible to calculate X_1. However, most of the trucks have the first axle spacing of 3.5m, which can be used in the calculations.

Axle spacing can be calculated more correctly at higher sampling rate. The other factors which are likely to be responsible for the errors in estimation are vehicle position, strain gauge errors and vehicle speed.

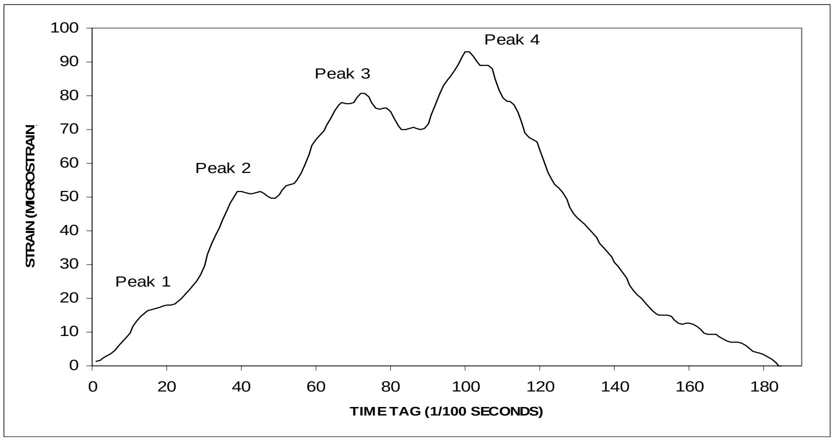

Figure 3 Field strain plot due to a four-axle-group truck

Determination of truck load

The calculation of truck load is based on the linear relationship between load and girder strain due to the axle weight. Figure 4 shows a load, P_1, advancing across a bridge of span L. The strain gauge is mounted at the point, SG.

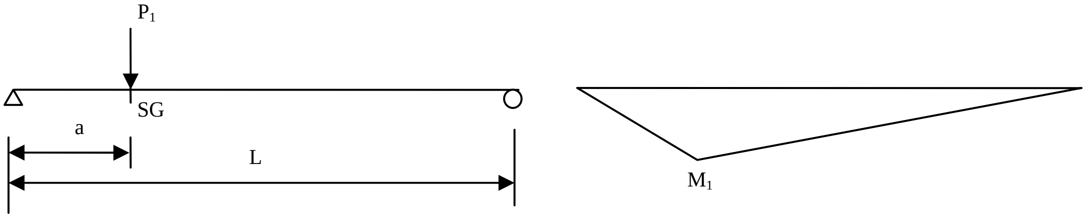

Figure 4 Moment due to one axle load moving across the point SG

The moment at the point SG, M_1, due to the load, P_1, is calculated by the following formula:

$$M_1 = \frac{a(L-a)}{L} P_1 \tag{4}$$

Where

L----The span of the bridge
a----- The distance of strain gauge from the left support

From the elementary small deflection beam theory, the bending moment, M_1, is also calculated as follows

$$M_1 = \frac{EI}{y} \varepsilon_1 \tag{5}$$

Where

E---- Modulus of elasticity
I ---- Moment of inertia
y-----The distance of strain gauge from the neutral axis.

From the above equations, the axle weight can be obtained as follows:

$$P_1 = \frac{EIL}{ya(L-a)} \varepsilon_1 \tag{6}$$

Or

$$P_1 = \varepsilon_1 C \tag{7}$$

Where,

$$C = \frac{EIL}{ya(L-a)} \tag{8}$$

When a truck with four axle weights is going through the bridge, the strain at the point, SG, is the superposition of the response due to each axle weight. When the second axle weight, P_2, just arrives at the point SG (Figure 5), the corresponding moment on SG can be calculated by the following formula.

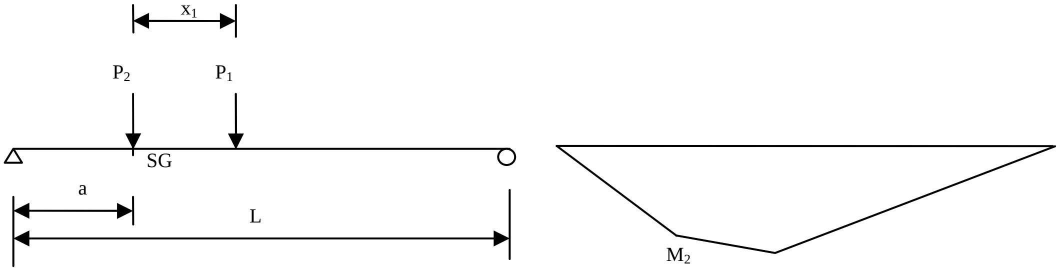

Figure 5 Moment due to two axle loads moving across the point SG

$$M_2 = \frac{a(L-a)}{L} P_2 + \frac{a(L-a-x_1)}{L} P_1 = \frac{EI}{y} \varepsilon_2 \qquad (9)$$

$$P_2 = \varepsilon_2 C - \frac{L-a-x_1}{L-a} P_1 \qquad (10)$$

As for the third and fourth axle weights, P_3 and P_4 the corresponding equations are as under:

$$P_3 = \varepsilon_3 C - \frac{L-a-x_2}{L-a} P_2 - \frac{L-a-x_1-x_2}{L-a} P_1 \qquad (11)$$

$$P_4 = \varepsilon_4 C - \frac{L-a-x_3}{L-a} P_3 - \frac{L-a-x_2-x_3}{L-a} P_2 - \frac{L-a-x_1-x_2-x_3}{L-a} P_1 \qquad (12)$$

The gross vehicle weight, GVW is calculated as follows:

$$GVW = \sum P_i \qquad (13)$$

This calculation has to be done for all the girders in the bridge. As already stated it is not easy to pick up strain corresponding to peak1. However, the time tag of this peak can be obtained from time tag of peak2 and going backwards by the time it would take the truck to travel 3.5m at the calculated speed. The peak1 strain could be then read from the strain data corresponding to this time tag. The peak strains would be clearly identifiable only in one or two girders in the bridge. The peak strains in other girders would have to be read from the field data corresponding to the time tags of clearly identified peaks.

When the vehicle speed exceeds 25 km/hr, the bridge is subjected to substantial dynamic magnification and the specific strain peaks might be higher than those due to the actual load. From the tests, we find that the gross weight calculated from the SHM matches the actual load very well.

Method in Model Analysis

We use a static model to simulate the performance of the bridge due to the truck passing through it. The program of Semi-continuum method of analysis for bridges (SECAN) is used to study the response of the girder, such as the moment, the stress and the strain, when the vehicle moves over the bridge from one end to the other end.

Method in Fatigue Analysis

Fatigue analysis uses the stress-life method. This method ignores the existence of cracks and employs S-N methods to predict fatigue lifetime, which builds a correlation between the number of loading cycles and the applied cyclic stress range.

IMPLEMENTATION

In order to verify the system and methodology, field data from the North Perimeter Highway Red River Bridge in Winnipeg, Manitoba, Canada was analyzed.

Bridge Description: North Perimeter Highway Red River Bridge, located on the north half of the Perimeter Highway that encircles the City of Winnipeg has ten spans. It has one span utilizing the second-generation steel-free deck technology. The steel-free concrete deck is supported on five steel girders as shown below.

Picture1 Steel Free Deck Span in the North Perimeter Highway Red River Bridge

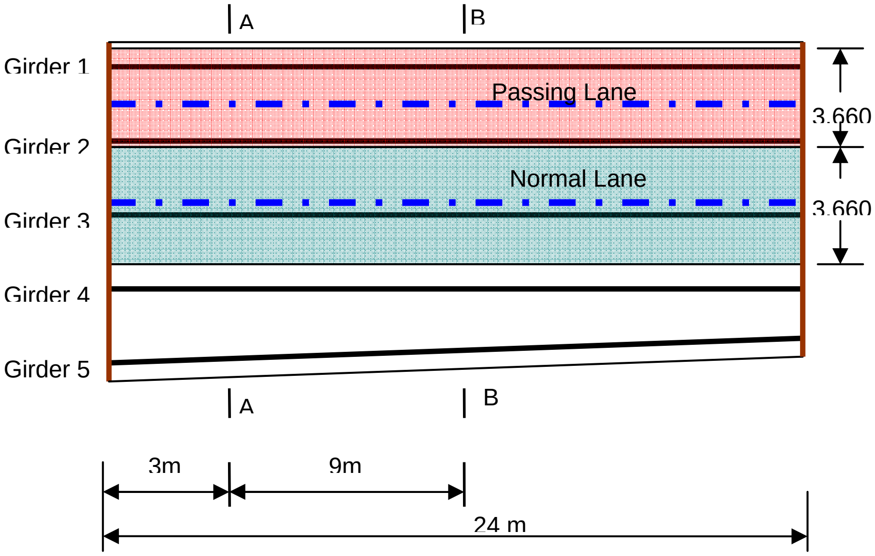

Figure 6 Layout of the North Perimeter Red River Bridge

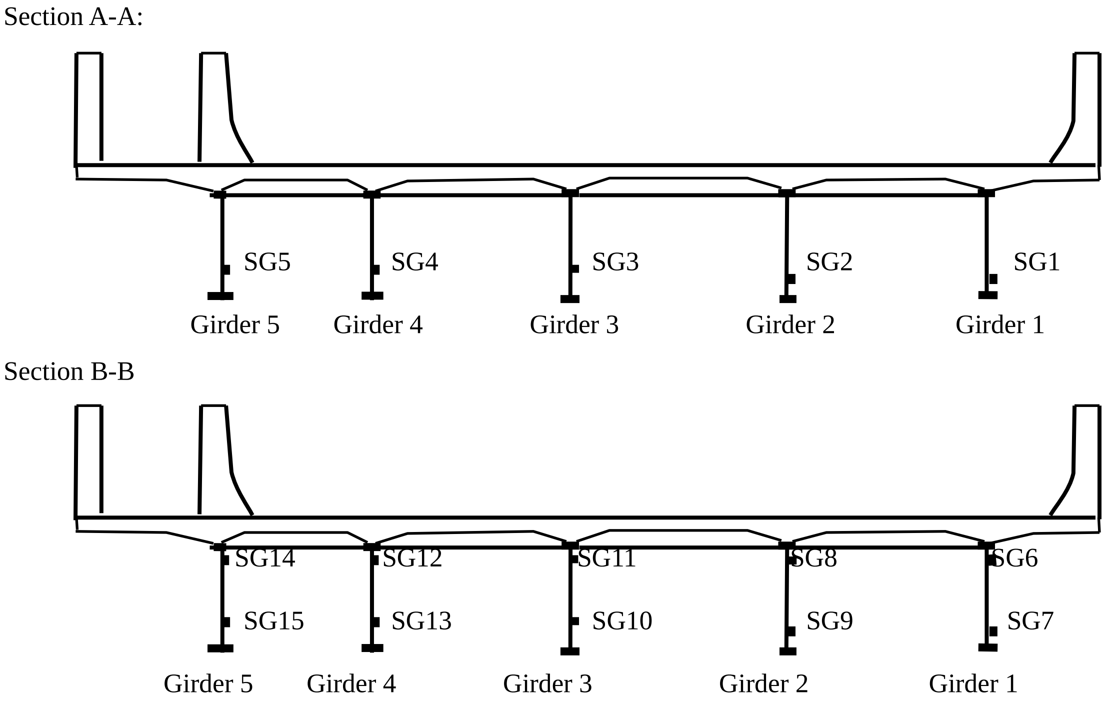

Figure 7 Cross-section of the North Perimeter Red River Bridge

Sensor system: The orientation of the North Perimeter Red River Bridge is roughly east-western. Five girders were instrumented at two sections identified in Figure 7 as A-A and B-B. A total of fifteen electrical resistance strain gauges were installed on the girders.

Data acquisition: Data from all the sensors are collected at a sampling rate of 100 readings per second and sent by the network to the server in the ISIS Canada at the University of Manitoba.

Field Data: We chose a set of strains on the Girder 1, which is on the passing lane. The sensors mounted on the sections A-A and B-B of this girder are designated as SG1 and SG7. Figure 8 is the plot of strains on Girder 1.

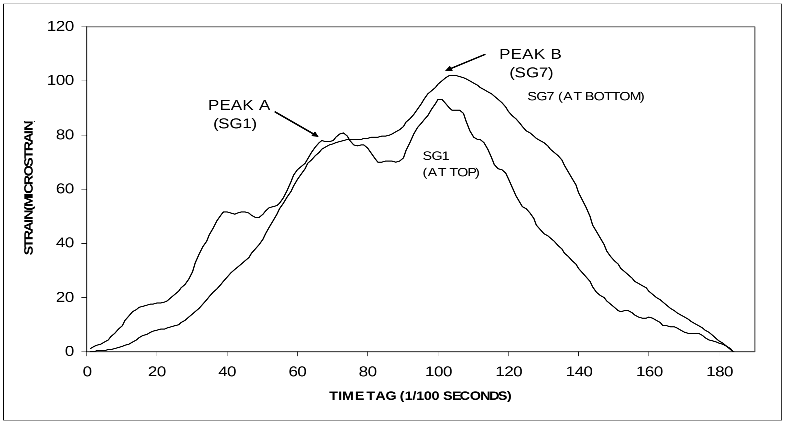

Figure 8 Plot of field strains on Girder 1

Truck Speed: SG1 in Fig. 8 exhibits four strain peaks which indicate that the truck moving across the bridge has four axle groups. The time interval between peak A and peak B is 38/100 seconds and X_g for the girder is 9 m. Using these parameters and equation (2) the truck speed, V, is calculated as 85 Km/hr.

Truck axle spacing: Because of the limited sampling rate of 100 sample points per second, some strain peaks might be missed and the error in the estimation of the truck axle spacing might be significant. The time intervals t_1, t_2 and t_3 between successive strain peaks for SG1 in Fig. 9 are 16/100, 28/100 and 35/100 seconds, respectively. Using these time intervals and equation (3) the axle spacings are calculated as under:

$x_1 = 3.79$ m $\quad x_2 = 6.63$ m $\quad x_3 = 8.29$ m

Truck axle weight: The field strains in the five girders near the support are shown in Figure 9. Based on these strains and utilizing the method proposed above with the known E, I, L, y and a, we get

$P_1 = 58$ kN $\quad P_2 = 113$ kN $\quad P_3 = 144$ kN $\quad P_4 = 179$ kN $\quad$ GVW = 494 kN

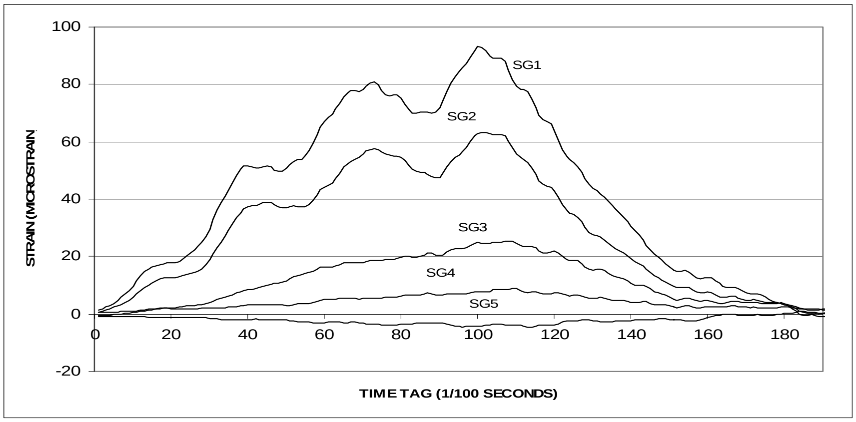

Figure 9 Strains in the five girders of the bridge

According to Weights and Dimensions Compliance Guide of Manitoba Transportation and Government Services [6], calculated GVW is close to the maximum GVW of the truck, 565 kN. The corresponding maximum axle group weights for a fully loaded four axle group truck are 55 kN, 170 kN, 170 kN and 170 kN. The difference between the calculated parameters and the actual loads might lie in the limited sampling rate, dynamic magnification and the noise in electrical measurements.

Load Sharing: The load shared by each girder as the truck passes over the bridge is plotted in Fig.10. The plot shows that most of the load is carried by girders 1 and 2. This information in conjunction with layout of the bridge shown in Fig. 6 can be used to conclude that the truck was in the passing lane of the bridge. Hence such plots can be used to determine the lateral location of the vehicles.

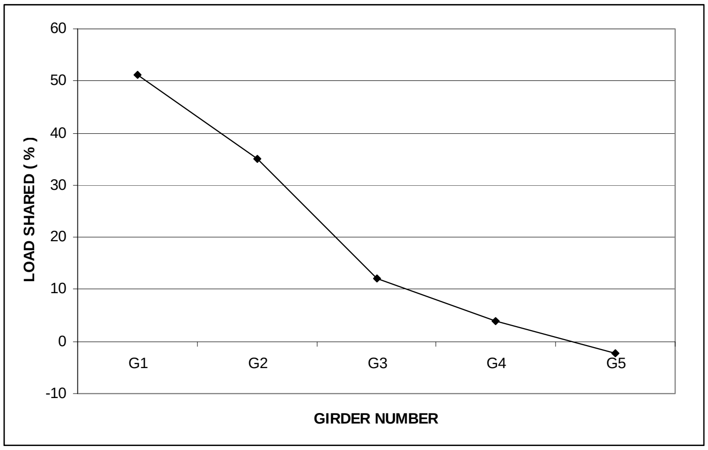

Figure 10 Load shared by the girders

Modeling: Figure 11 shows the comparison between the field data for a four axle group truck and the SECAN result for a four axle group standard truck with a maximum gross vehicle weight of 565 kN, traveling at 85 km/hr. The lower strains in the field data could be attributed to the fact that the horizontal bearing force may not be zero as assumed in the calculation of ‘C’. Therefore ‘C’ should be determined by passing a known axle weight truck on the bridge. The two plots exhibit similar behavior as for as the strain peaks are concerned. Since the results from SECAN show agreement with the field monitoring data, it can be surmised that the analysis model and the model parameters represent the actual truck load and the structural behavior under investigation. This allows us to calculate the stress and to estimate the remaining fatigue life.

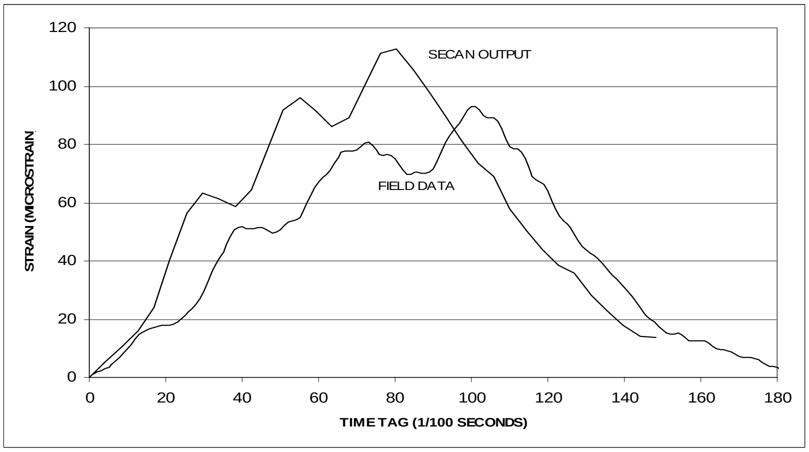

Figure 11 Comparison of the field data and SECAN result

Fatigue analysis: Stress is the output of SECAN and the input for fatigue analysis based on stress-life method. We choose the stress over the supposed range, such as approximately 60% of the ultimate load previously determined by the laboratory test or the designed code. This is part of the work is still in process.

CONCLUSION AND FUTURE WORK

This paper introduces a new method based on *civionics* engineering that incorporates WIM and SHM for the in-situ monitoring of civil infrastructure. The combination of the two methods makes it possible to create an integrated system to evaluate the vehicle parameters, study the bridge performance and estimate the remaining fatigue life. Sample results on the North Perimeter Red River Bridge demonstrate that the analysis technique is valid in identifying the vehicle parameters for a simply-supported linear bridge. Even so, the following aspects require further study.

1) Sample rate is an important consideration in the calculation of the vehicle parameters, such as vehicle speed, vehicle configuration and vehicle load. Higher sample rate may be required for vehicles traveling at higher speeds. To evaluate the axle weights more correctly, the sensors design is a critical concern and needs more investigation..

2) Model for analyzing the behavior of the girder should be developed and updated to dynamically stimulate the actual structure. Future work will include the development of a dynamical analysis program to assess the response of the structure and to compare with the field data to estimate the health of the structure.

3) The work on in-situ fatigue analysis is under progress.

In addition, intelligent software systems should be developed and updated to process and assess the fatigue life of the infrastructure based on collected field data. Also, computer simulations provide a useful method for replacing expensive field tests when it comes to estimating structural behavior; however, they fail to reproduce environmental effects.

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