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Direct Field Measurement of the Dynamic Amplification in a Bridge

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Abstract

In this paper, the level of dynamics, as described by the Assessment Dynamic Ratio (ADR), is measured directly through a field test on a bridge in the United Kingdom. The bridge was instrumented using fiber optic strain sensors and piezo-polymer weigh-in-motion sensors were installed in the pavement on the approach road. Field measurements of static and static-plus-dynamic strains were taken over 45 days. The results show that, while dynamic amplification is large for many loading events, these tend not to be the critical events. ADR, the allowance that should be made for dynamics in an assessment of safety, is small.

Key words: field testing, bridge assessment dynamic ratio, fiber optic, weigh-in-motion

1. Introduction

Accurate bridge safety assessment requires knowledge of load effects as well as the structure's capacity to resist these effects. Allowances for dynamic amplification of load effects are often conservative. Hence, better information on the magnitude of dynamic amplification has the potential to reduce the number of bridges that are prematurely repaired or replaced. This paper describes a study where the dynamic allowance for a bridge is directly measured on site.

Many studies have considered the dynamic impact factor for bridges subject to passing trucks [1-3]. The magnitude of the amplification of stress due to vehicle-bridge-interaction (VBI) is often studied using the Dynamic Amplification Factor (DAF) [4-6]. DAF is defined as the ratio of the total load effect (including dynamics) to the static load effect for a particular loading scenario on the bridge. DAF has been used in many studies [7-12] for quantification of the dynamic increment of load effect on the bridge.

Paeglite and Paeglitis [13] present a study of the DAF obtained from the results of dynamic load tests of bridges carried out from 1990 to 2012 in Latvia. The DAF values were obtained from the dynamic response measured using an optical vibration sensor. The values of DAF obtained were analyzed and compared to the values used in the definition of the Eurocode 1 traffic load model. The actual DAF values for a good quality bridge deck surface were, in most cases, less than the values incorporated in the Eurocode [14].

O'Brien et al. [15, 16] suggest that DAF does not recognize the reduced probability of both maxima occurring simultaneously, i.e., static load effect and dynamic amplification. They point out that the maximum values of DAF tend to result from lighter vehicles and are not relevant when seeking characteristic maximum values and propose the concept of Assessment Dynamic Ratio (ADR). ADR is defined as the ratio of characteristic maximum total load effect, to characteristic static load effect, which, in general, correspond to different loading scenarios. For both total and static effects, the characteristic value is the expected maximum, over all possible cases, for the specified return period. This ADR is more appropriate for dynamic assessment since it provides the Engineer with the ratio of what is needed, to what can be found by static probabilistic analysis [17].

Previous research using ADR found the "expected level of lifetime dynamic interaction" for a certain site and bridge to be approximately 1.06, significantly lower than the DAF prescribed in the Eurocode [18]. González et al. [19] report that ADRs below 1.1 are typical for bridges with very good road profiles while González and Žnidarič [20] found that ADR, like DAF, tends to decrease with an increase in load. Both Enright et al. [21] and Caprani [12] state that the implication of such values for dynamics being much lower than expected is that the governing loading scenario for a majority of bridges is altered.

Caprani et al. [22] utilize multivariate extreme value theory in conjunction with static simulations and finite element vehicle-bridge dynamic interaction models to simulate static and total load effects for the Mura River Bridge in Slovenia. It is shown, for this bridge and traffic, that the required allowance reduces with increasing load effect. Consequently, the dynamic allowance is significantly less than recommended by bridge codes in this case.

Cantero et al. [23] extend the concept of ADR to railway bridges. Guidelines are provided in [24] and [25] on how to obtain a site-specific value for dynamic allowance, both numerically and by field measurement. A Bridge WIM system was used to record the total response and to infer the static response of about 74 000 5-axle trucks over the course of a 58-day period. The measured total and inferred static bending moment for this population of vehicles is used to find the site-specific ADR value for a 50-year return period. It is shown that measured and numerically simulated data produce similar ADR values. However, it should be noted that, as static effects are inferred from the same sensors used to measure the total effects, there is a risk of bias. This risk is considered in [21] and numerical simulations suggest that the bias is small.

Whereas other investigations into ADR extrapolated the characteristic load effects using extreme value theory [16] simulated 10 000 years of traffic which allowed for an interpolation of load effects. It is reported in [24] that variability of ADR decreases as the sample size increases.

In this paper, the static axle weights of passing vehicles are found using a piezo-polymer weigh-in-motion (WIM) system and the corresponding load effects found using the bridge influence line. The total load effects (including dynamics) are measured directly using fiber optic sensors on the bridge.

2. Weigh in Motion and Influence Line

2.1. Data Collection and Site

A bridge structure at Loughbrickland in Northern Ireland, United Kingdom (UK), was instrumented with fiber optic sensors. The bridge span is 18.8 m with a skew of 22.7° (Fig. 1). The beam-and-slab structure (Fig. 2) is typical of many short-span new-build bridges across the UK and Ireland. The superstructure consists of 27 no. prestressed concrete Y4 girders, each 1 m in depth, spaced at 1.22 m centers. The prestressed beams work compositely with a 200 mm overlaid cast in-situ concrete deck. The deck is supported by permanent glass reinforced concrete formwork, spanning transversely between the main beams. The abutments are supported by a pile cap which is integral with the deck beams.



Figure 1: Side elevation of Loughbrickland site.

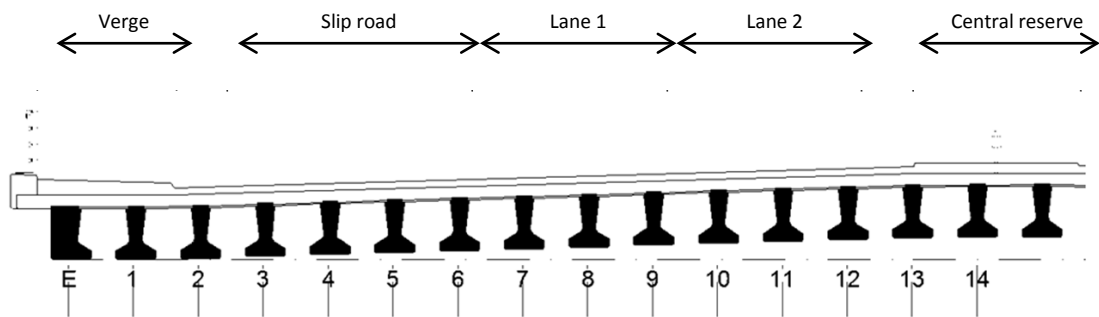


Figure 2: Section showing northbound carriageway.

The bridge structure forms part of the main Dublin to Belfast A1 road which was constructed in 2010. This route is ideal for an analysis of Heavy Goods Vehicles as it is an important link between the ports of Dublin, Warrenpoint and Belfast and forms a strategic cross-border economic link between Northern Ireland and the Republic of Ireland. The structure is on a central route through the island and has a high traffic volume. There are 10 000 to 12 000 vehicles travelling on the carriageway in each direction daily. The bridge also provides an underpass to give access to the southern end of the town of Loughbrickland. The traffic can pass under the main A1 carriageway and travel onto the B3 Dublin/Grovehill Road (Fig. 3).

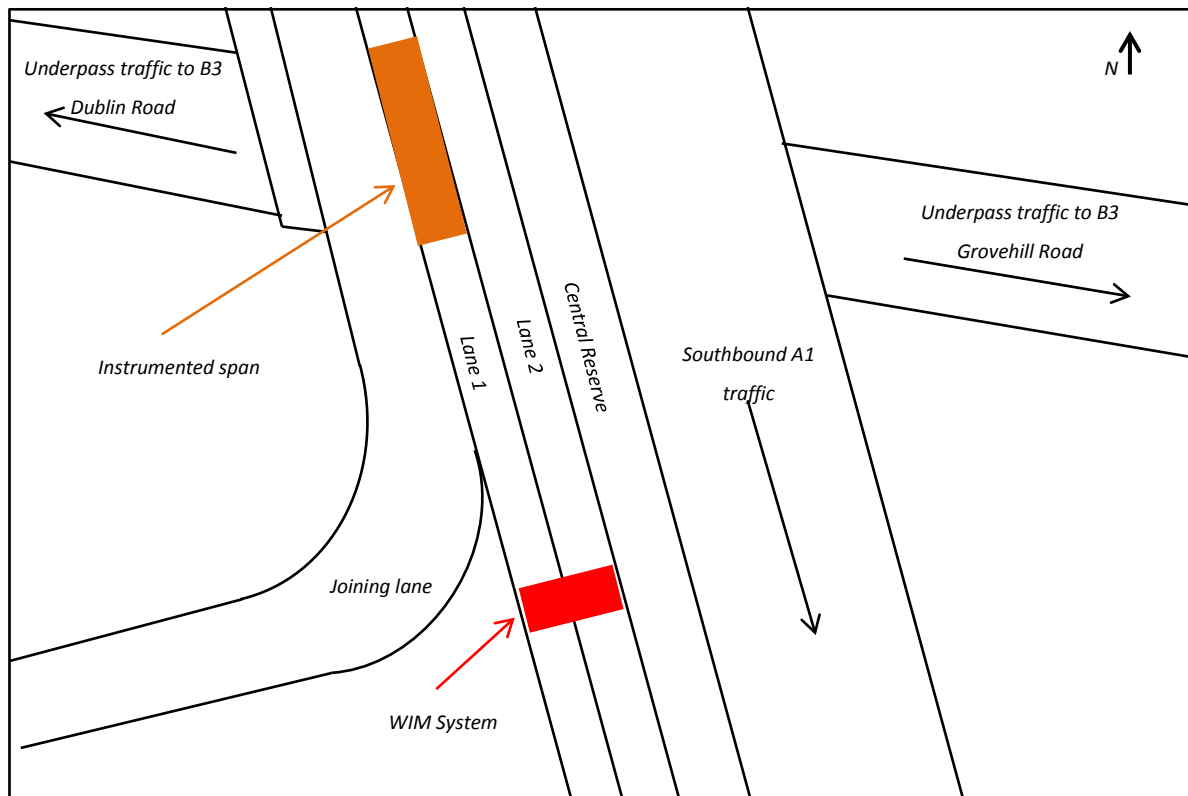
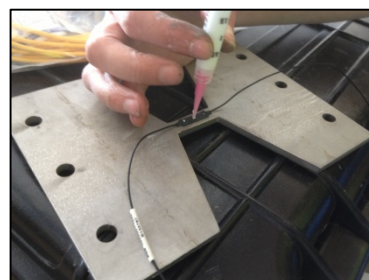


Figure 3: Site layout.

The bridge carries four traffic lanes, two in each direction, as well as two peripheral lanes for traffic joining/exiting the carriageway, as shown in Fig. 2. A large central reserve separates the north- and south-bound carriageways; the northbound section was chosen for instrumentation.

Fiber optic sensors were installed on Beam No. 6 (Fig. 2). Three sensors were installed in parallel, each on mechanical strain amplifiers as illustrated in Fig. 4. The mechanical amplifiers – simple plates in a 'dog-bone' shape – served the function of concentrating most of the movement over their 150 mm length at the sensor location. The strains from three such amplifiers were averaged to further improve the resolution. The strain was output to the nearby control cabinet and saved for every six minutes of data. There is a 6 second delay between the end of one record and the beginning of the next.



(a) (b)

Figure 4: Mechanical strain amplifiers (a) in place on the bridge, (b) bonding of strain gauge to amplifier.

A piezo-polymer pavement Weigh-in-Motion (WIM) system was embedded in the pavement on the approach to the structure (Fig. 5). The system can provide detailed information on the passing traffic including; gross weight, axle weights, axle spacings, temperature, speed and number of axles. This information was subsequently used for the estimation of static load effects for each loading event.

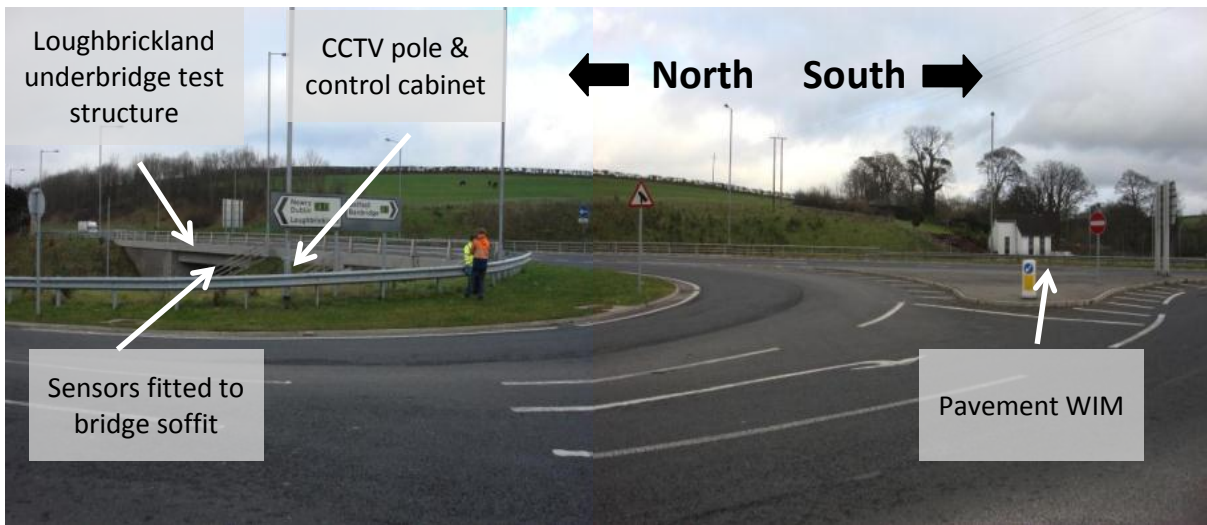


Figure 5: Overview of site and test structure.

2.2. Measured Influence Line

An influence line with high accuracy is required for the estimation of the static load effects for all events. The structure’s response to seven calibration trucks of known weight was used to infer the influence line from real measurements. One of the factors in choosing the site was the bridge's proximity to a static weigh station located just outside Loughbrickland Village at its northern end. This weigh station is used by the Driver and Vehicle Agency of Northern Ireland (DVANI) to check the weights of vehicles using the dual carriageway. The gross vehicle weight (GVW) and axle weights of the calibration trucks were measured statically at the weigh station and are given in Table 1.

Table 1: Calibration truck properties.

Truck No.	No. of axles	Gross weight (kg)	Axle weights (kg)					
			1	2	3	4	5	6
1	4	14 100	4200	3700	2900	3300	-	-
2	5	13 300	4800	3300	1800	1800	1600	-
3	5	24 500	5300	6500	4100	4400	4200	-
4	3	10 000	3900	3800	2300	-	-	-

5	2	8 700	4600	4100	-	-	-	-
6	5	30 200	5800	8400	4000	5600	6400	-
7	6	35 100	5600	2400	7100	6500	7000	6500

The strain signal for Beam No. 6 due to the passage of the first calibration vehicle is shown in Fig. 6.

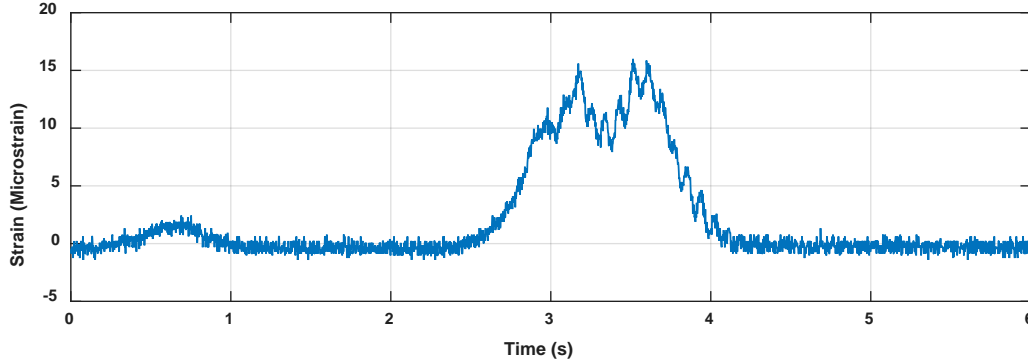


Figure 6: Strain in Beam 6 due to Truck No. 1.

To calculate the influence line corresponding to the passage of each calibration truck, the method developed by OBrien et al. [26] is adopted. This uses the same principle developed by Moses [27] to find unknown axle weight using a known influence line (Bridge WIM). An error function is defined as the sum of the squares of the differences between the measured and theoretical load effects:

$$E = \sum_{k=1}^K (\varepsilon_k^M - \varepsilon_k^T)^2 \quad (1)$$

where ε_k^M and ε_k^T are the k^{th} measured and theoretical strains respectively and K is the number of scans. The theoretical strain is a function of the axle loads and the corresponding influence line ordinates. In Bridge WIM the error function is differentiated with respect to the unknown axle weights and set to zero to minimize the error function. Here, the error function is differentiated with respect to each ordinate of the influence line. For the k^{th} ordinate,

$$\begin{aligned} \frac{\partial E}{\partial I_k} = & 2[\varepsilon_k^M - (W_1 I_k + W_2 I_{k-t_2} + W_3 I_{k-t_3} + W_4 I_{k-t_4})](-W_1) \\ & + 2[\varepsilon_{k+t_2}^M - (W_1 I_{k+t_2} + W_2 I_k + W_3 I_{k+t_2-t_3} + W_4 I_{k+t_2-t_4})](-W_2) \\ & + 2[\varepsilon_{k+t_3}^M - (W_1 I_{k+t_3} + W_2 I_{k+t_3-t_2} + W_3 I_k + W_4 I_{k+t_3-t_4})](-W_3) \\ & + 2[\varepsilon_{k+t_4}^M - (W_1 I_{k+t_4} + W_2 I_{k+t_4-t_2} + W_3 I_{k+t_4-t_3} + W_4 I_k)](-W_4) \\ = & 0, \\ & k = 1, 2, \dots, K \end{aligned} \quad (2)$$

where t_i is the number of scans between the passage of axles 1 and i . Solving these linear equations in the K unknowns, $I_k, k=1, K$, gives the influence line which best fits the measured response. While Eq. (2) applies to a 4-axle truck; similar equations exist for trucks with other numbers of axles.

Information on the vehicle speed and axle spacing was taken from other sensors located in the pavement WIM system. A unit influence line for each of the seven calibration vehicles was found. The average of these values was then calculated and is illustrated in Fig 7. A moving average filter was then applied to the mean influence line, as proposed by González et al. [28] and this was deemed to be the final ‘measured’ influence line. As all of the calibration trucks traveled in the slow lane (lane 1 in Fig. 2), this influence line is only valid for trucks in that lane.

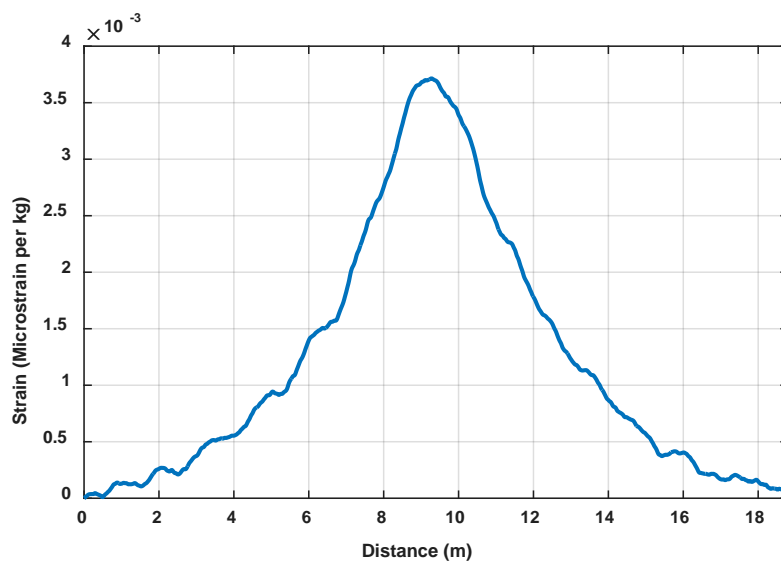


Figure 7: The unit influence line estimated from all seven calibration trucks.

3. Weigh-in-Motion data

Data from the piezo-polymer WIM system was found to be temperature sensitive and to drift over time. The mean steer axle weight in standard 5-axle trucks was found to be correlated with temperature, suggesting that temperature compensation was not enabled in the system or it was not operating correctly. In addition, the distribution of steer axle weights for these trucks tended to decrease over time, even for trucks weighed at the same temperature – see Fig. 8.

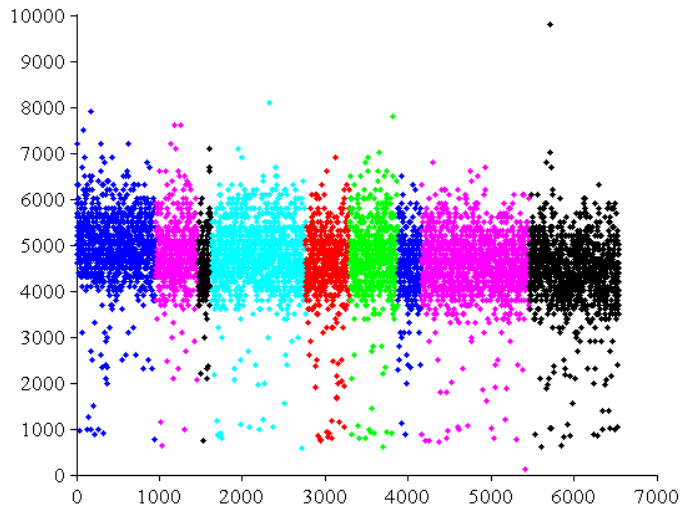


Figure 8: Time drift of steer axle weights measured at 10°C (vehicles are given in chronological order; colors indicate different months)

The static response of Beam 6 to the passage of each truck is calculated as a linear combination of axle weights and the corresponding influence line ordinates from Fig. 7. To correct for temperature and drift, the calculated static response is scaled to best fit the measured total response. This is illustrated in Fig. 9. In effect, the WIM system is only being used to determine the *relative* weights of the axles of each truck while the fiber optic sensors are being used to determine the gross weight. The dynamic component is then defined as the ratio of the maximum measured total strain to the maximum scaled static strain.

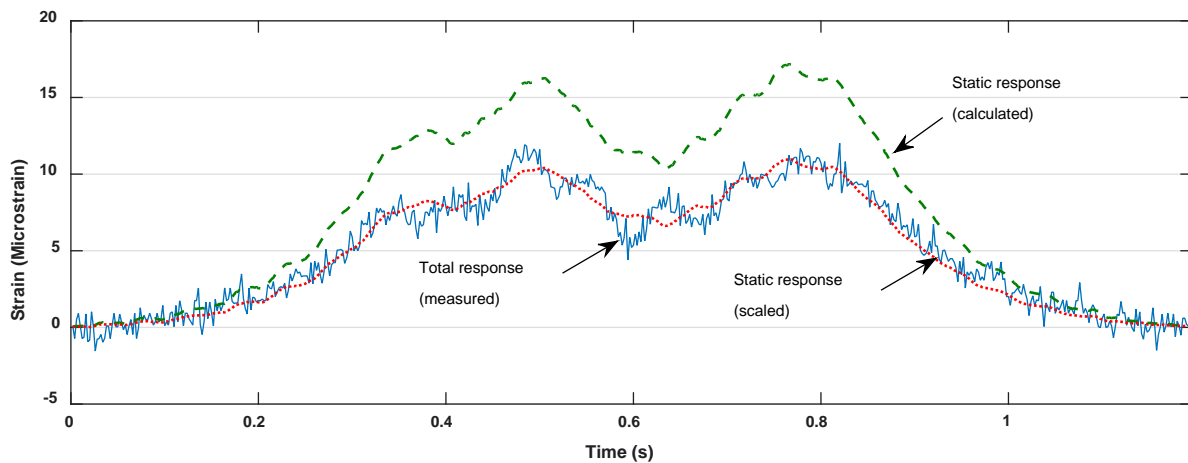


Figure 9: Fitting of the static response to the total response.

4. Results and Discussion

4.1. DAF and ADR

The measurements were carried out from March 15th to April 28th, 2015. The WIM data and the measured strain data were gathered and synchronized. Only events with trucks heavier than 10 tonnes were considered. For reference, the DAF values are calculated for all the events measured through the 45 days and are shown in Fig. 10. The DAF values out of the range of 0.8 to 2.0 are removed as most of them are the result of error in the scaling process explained above. It can be seen that most values are in the range 0.9 to 1.6.

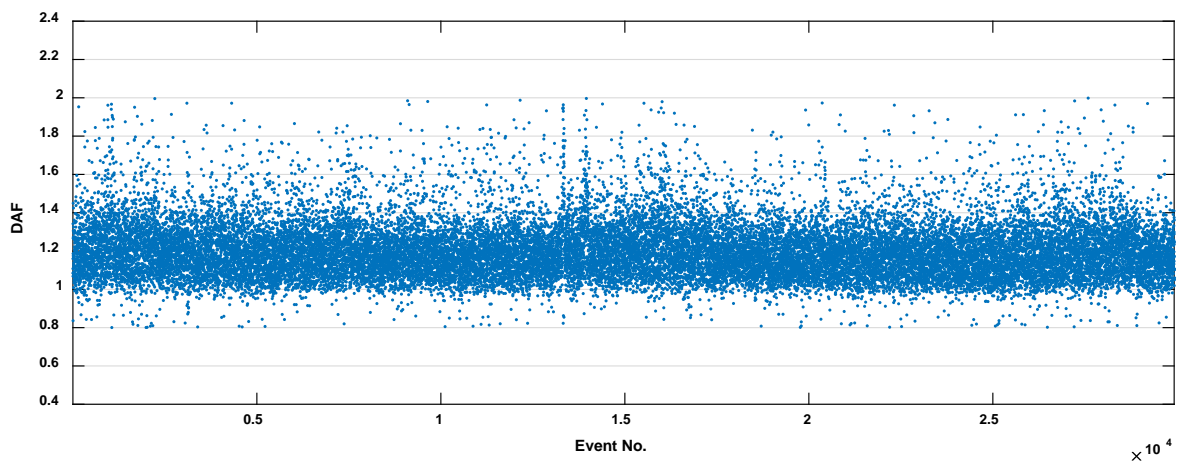


Figure 10: Dynamic Amplification Factor (DAF) calculated over 45 days.

Fig. 11 shows the plot of total versus static load effect for all the events. It illustrates that many of DAF values in Fig. 10 correspond to events with lower magnitude load effect. DAF is the slope of a line joining the origin to the point representing the event in Fig. 11. A linear regression to these points shows that the points are getting closer to the diagonal as the strains get larger, i.e., the mean DAF tends towards unity as strain increases.

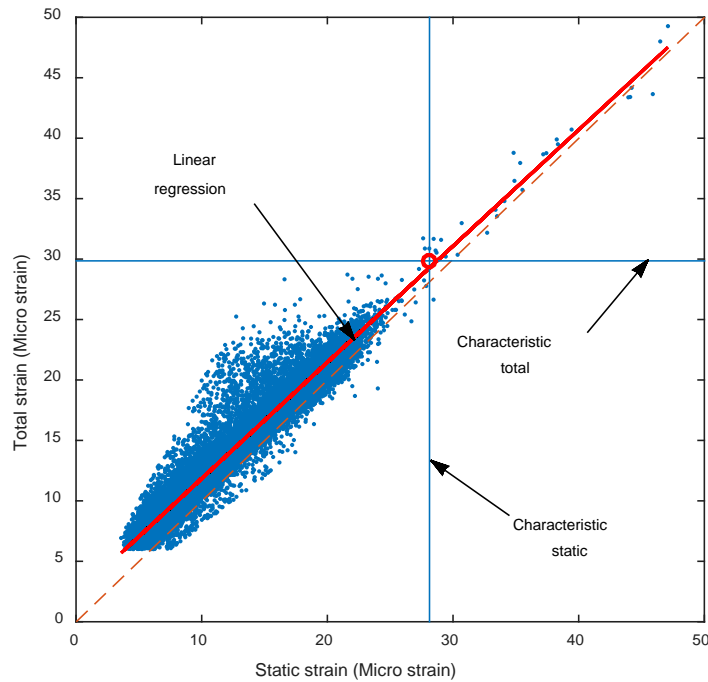


Figure 11: Total versus static load effect. ADR is a function of the return period considered – the 99.9% ADR is the slope of a line joining the origin to the small circle.

The characteristic total with 99.9% probability of non-exceedance is 29.85 while the 99.9 % characteristic static strain is 28.11. The ADR corresponds to the point where characteristic total meets characteristic static and is 1.062. This can be seen to be considerably less than the DAF values recorded (Fig. 10), which generally correspond to smaller strains.

The Beam 6 strains are plotted on Gumbel probability paper in Fig. 12. As expected, total strain exceeds static in general but there are a small number of exceptions. In particular, it can be seen that the 3rd, 4th and 5th largest static strains exceed the 3rd, 4th and 5th largest total strains. It should also be noted that there is a general trend of decreasing dynamics with increasing static load and this is expected [15, 16].

The changing slopes in the curves suggests data consistent with statistical mixtures of event types, likely corresponding to different types of truck. Best fit trend lines are fitted to each segment of data, as shown in the figure. The 99.9% characteristic values correspond to the final group of trucks (the heaviest ones), as can be seen in Fig. 12(b).

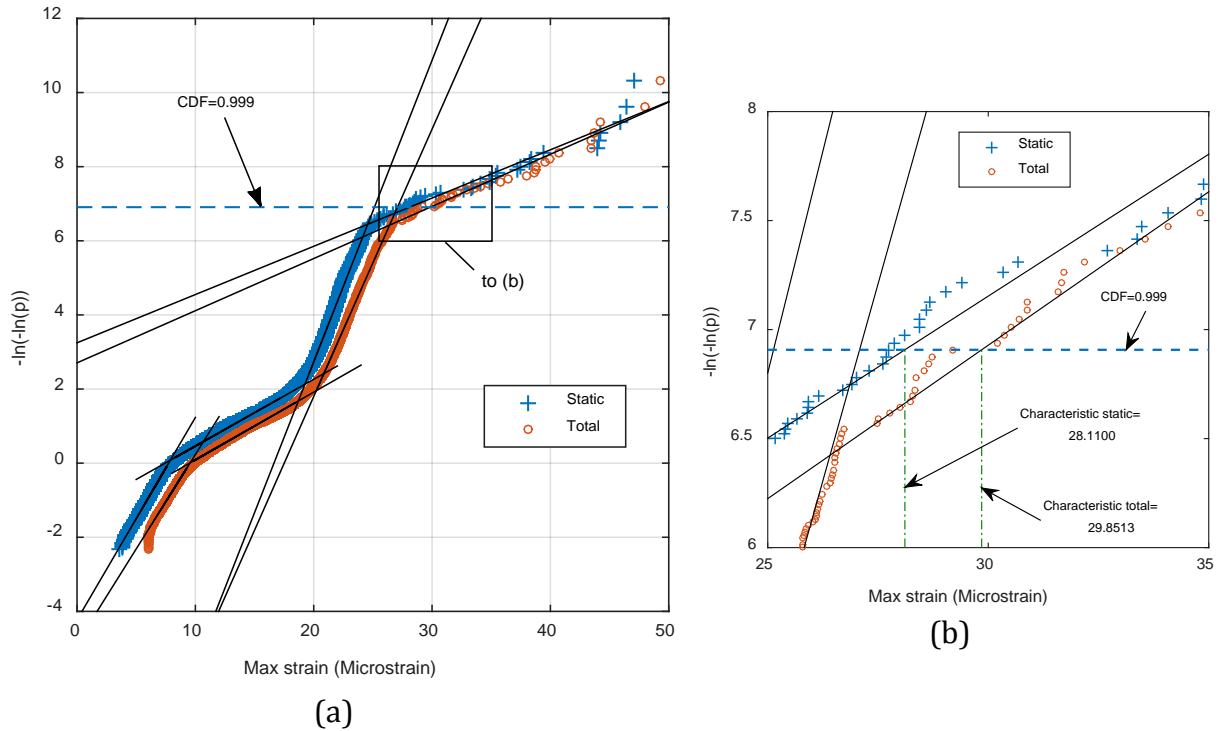


Figure 12: Gumbel probability plot; (a) full plot, (b) a zoom view.

4.2. Conclusions

In this paper, the dynamic amplification at a point in a bridge beam is determined from field measurements. Total strain is measured directly using fiber optic sensors. Static strain is measured from a piezo-polymer WIM system, scaled to remove the influence of temperature and drift. The WIM weights are converted to strains using an influence line inferred from the response to trucks weighed at a static weigh station. Dynamic Amplification Factor (DAF) is shown to be inappropriately high, driven by a large number of lighter trucks. Assessment Dynamic Ratio (ADR) is defined as the ratio of characteristic total to characteristic static strain and is found to be significantly less.

5. Acknowledgements

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Figure Captions:

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