LIVE LOAD RATING BY INCLINATION MEASUREMENT OF A STEEL BRIDGE INCORPORATING RELIABILITY ANALYSIS

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1. INTRODUCTION

Bridges in Japan are aging nowadays because of the high construction activity about 50 years ago. In this context, evaluate the performance of existing bridges have become a substantial topic recently. Nevertheless, visual inspections of superstructures are not sufficient to take maintenance decisions such as truck weight limitation, retrofitting or closing of the bridge. That is why a more accurate and quantifiable way to evaluate existing bridges is necessary. In the United States of America, the Manual for Bridge Evaluation and its Load & Resistance Factor Rating (LRFR) [1] is the specification for existing bridges evaluation. The performance is quantified using a Rating Factor (RF, Eq.1) which is the nominal resistance (R_n) minus the dead load nominal value (DL) over the live load nominal value (LL) corrected by their respective safety factors.

$$RF = \frac{\phi_R R_n - \gamma_{DL} DL}{\gamma_{LL} LL} \quad (1)$$

If the rating factor is higher than 1, the structure evaluated is considered safe against live load. The live load safety factor is evaluated from the daily traffic volume and the resistance one is updated from the general condition of the member. However, only small changes can be made for those factors. This method does not seem to be neither accurate nor take advantage of the possibility of measuring on the existing member. Also, the safety factors are usually higher than the ones used in design even though one should have less uncertainty on an existing structure than one at a design stage. Given this background, a more accurate rating of an existing structure using in-service data will be attempted.

2. LIVE LOAD UPDATING

The structure studied is a highway bridge of Tokyo Metropolitan Expressway. The superstructure is composed of steel members and a reinforced concrete slab above it with a span of 31.2 meters (figure 1). Its main girders will be evaluated in this research.

In order to update live load nominal value and safety factor, inclination data near bearing is used. Strain or deflection at mid-span might appear as a more logical effect to evaluate the live load.

However, deflection is a quantity very difficult to measure directly and deducing it from acceleration or velocity data can produce errors and inaccuracies in the results from the integration process. Strain is also difficult to measure for a long time. One the other hand, inclination can be directly deduced from 3-axis acceleration data (Eq. 2) applying an arctangent function after a low-pass filter, easy to measure for a long time given the wide range of accelerometers available recently for wireless and low-power consuming functions. Moreover, the dead load could also be evaluated at the same time as the constant contribution in the inclination time series.

$$\theta_{flexion} = \arctan\left(\frac{A_{longitudinal}}{A_{vertical}}\right) \quad (2)$$

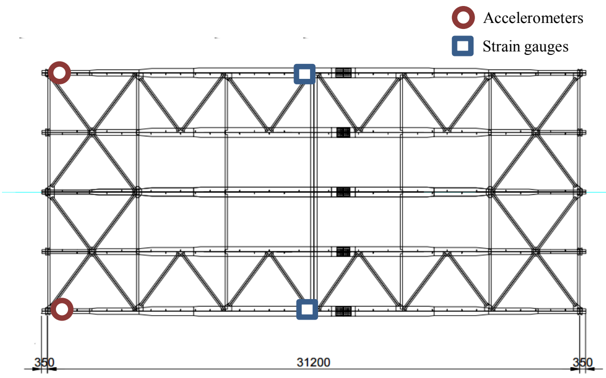

Figure 1. One span superstructure of the studied bridge

From extreme experimental events measured continuously during a certain length of time, one can evaluate the future maximum extreme value and its statistical distribution. In the case, extreme value measurements are the inclination peaks due to vehicles and the duration of measurements will be weeks or days while the return period will be 5 years which is the time span between two periodic inspections. To do so, Extreme Value Theory (EVT) can be used [2]. A threshold value is set and all the peaks above this value are extracted as a sample of all the inclination peaks due to live load from the measurement. From this sample, the parameters of the upper tail of the General Pareto Distribution (GPD) are fitted in order to infer a future 5-year maximum inclination value. This distribution is the one which fits best extreme values and maximum problems when data is extracted as peaks over a threshold. However, this theory is usually applied on long term phenomena like meteorological issues where data are gathered for years and the return level calculated for centuries. To ensure that this statistical model suits the data, one can generate the Probability Plot and the Quantile Plot which are tools to compare the fitted GPD and the Empirical distribution of the sample.

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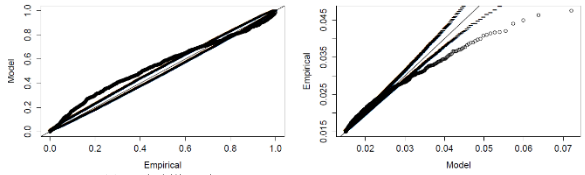
Figure 2 represents the results obtained from 24 hours continuous inclination data gathered on one of the external girders in 2009. The plots on top are the Probability plot and Quantile plot. As one can see, the plots are not linear but close enough to consider that the model fits the data according to observations of the same plots for other kind of physical phenomena considered well modeled. On plot (c), one can observe the density fitted from the sample. On plot (d), one can see inference for return level of maximum inclination for the year after the measurement. Finally, the 95% confidence interval obtained for the 5-year inclination return level is $\theta_{LL} = [0.218°, 0.260°]$.



(a) Probability Plot (b) Quantile Plot (c) Density Plot (d) Return Level Plot

Figure 2. Inclination inference results from EVT

3. FROM PROBABILISTIC TO SEMI-PROBABILISTIC POINT OF VIEW

By getting the variance and the mean of the future maximum Live Load using the previous method, one can obtain the nominal value of the live load and its safety factor by reliability theory. A target probability of failure is expressed as a reliability index:

$$\beta = \psi^{-1}(P_{failure}) \tag{3}$$

$\psi(.)$ is the cumulative distribution function of the normal reduced centered distribution and $P_{failure}$ represents the probability of failure. The target is determined from a social-economical study – it should reflect a compromise between safety and cost to optimize the profit for society. If the reliability index of the structure is higher than the target, it is considered safe. By identification of factors between the probabilistic point of view which compares the structure reliability index and the target, and the semi-probabilistic point of view, i.e. comparison between resistance and loads affected by safety factors), one can obtain a relationship between safety factors, probabilistic properties such as mean and variance of resistance and loads and the target reliability index. This way, the nominal value and safety factor for the live-load are obtained and the Rating Factor can be updated from extreme value theory results.

4. RESISTANCE IN TERMS OF INCLINATION

There is one remaining issue. Usually, in specifications, resistance is expressed in terms of stress, strain or deflection. To compare them with the loads effects (inclination) we deduced, it is necessary to express it in terms of inclination. The idea is that this yield angle is the inclination produced by a moving truck that would also produce the yield stress (figure 3). A 10 ton moving load has been applied on the girder using the finite element software ABAQUS and the ratio between maximum inclination and maximum stress obtained has been used as a conversion coefficient between yield inclination and yield stress of the member.

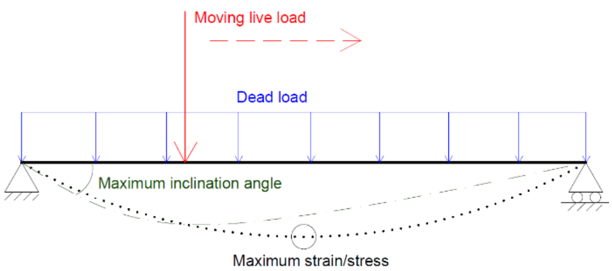


Figure 3. Principle to convert yield stress into yield angle

Nevertheless, from structural mechanics, the concentrated load over uniform load ratio, equivalent live load/dead load ratio, has an influence on the resistance expressed in terms of inclination. Hence, more calibration and testing of more realistic loading by simulated moving trucks, by not only one single load, but also different load amplitudes is necessary. However, the results already look quite promising. The final rating factor is $RF_{inclination}$=1.89. The Extreme Value methodology have been reproduced with strain data collected at the same time as the inclination data and performed the bridge evaluation in terms of strain. A rating of RF_{strain}=2.06 have been obtained which is very close to the one calculated using inclination and higher than the one obtained from the US Specifications' LRFR (RF_{LRFR}=0.87, calculated with USA truck specifications).

5. CONCLUSIONS

Inclination is considered an exploitable type of data for bridge evaluation as strain and quite convenient to collect on site. Test in several days or weeks could help to predict the load condition of 5-years return period by EVT. Resistance expressed as inclination still needs to be refined. Finally, a methodology to update the resistance of a member is to be determined using for instance acceleration data and dynamic properties in order to fully update the rating factor.

REFERENCES

[1] AASHTO (2013): 2013 Interim Revision to Manual for Bridge Evaluation, Second Edition 2010, American Association of State Highway and Transportation Officials

[2] S.Coles (2001): An Introduction to Statistical Modeling of Extreme Values, Springer-Verlag