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Application of a new method for probabilistic fatigue analysis from strain measurements on bridges

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Abstract. Increasing loads, ageing of materials as well as environmental change make the issue of fatigue damage critical on bridges, especially in the case of old steel or iron structures. The assessment of the fatigue loads on specific elements of these assets can be carried out from on-field strain measurements with the application of classical methods involving rainflow cycle counting and the use of Palmgren-Miner's rule.

However, such a fatigue assessment suffers from significant uncertainties about the real fatigue damage ratio and the consecutive residual fatigue life. A new probabilistic method for fatigue assessment is proposed, as the result of a joint research by OSMOS Group and École des Ponts. The theoretical background of the method is described, involving a probabilistic formulation of Miner's rule and the use of a Weibull model to describe the health of structural elements.

Real field case studies are presented, on two historical iron truss road bridges in France, with a dataset of more than 18 months of continuous strain measurements used for the fitting of the probabilistic model of fatigue loads. The incidence of the quantity of data and of the number of sensors used for the analysis is discussed, along with the conclusive results concerning the probabilistic description of the residual fatigue life.

Keywords: Fatigue, Road Bridge, Traffic Load, Structural Health Monitoring, Strain Analysis.

Introduction

With ageing infrastructure, increasing road traffic and limited budget for maintenance, asset managers need gathering comprehensive and continuously updated information on road bridges. Structural Health Monitoring (SHM) is a way to collect continuous measurements of quantities like strain and vibrations on critical parts of the bridges, and to analyze these data to deliver a synthetic useful information [1].



Fatigue analysis is one of the possibilities associated with continuous strain measurements, particularly in the case of metal bridge decks under the effect of repeated traffic loads. It allows to estimate the cumulated damage rate due to fatigue and thus to have an insight into the remaining fatigue lifetime of the asset. Such a methodology has been widely documented using deterministic or semi-probabilistic approaches, and with SHM data as an input instead of conventional fatigue loads [2].

However, mastering the uncertainties on a result given from real on-field SHM data still represents a challenge, because of the discrepancy of the load cycles and of the heterogeneity of fatigue resistance of each piece of building material. To address this issue, OSMOS and École des Ponts have been involved in a common research action for the last years, which delivered the formulation of a new probabilistic method for the fatigue assessment of metallic structures [3]. This formulation has been put in practice to investigate the fatigue life of a mobile crane in an industrial site in [4].

This contribution paper reports a particular case study on two historical iron-truss bridges, initially designed for light local traffic in the nineteenth century, over the Loire River in France. The data gathering took place in the frame of the “GeRICO” research project, supported by the French government and steered by the Cerema as part of the “Programme National Ponts”. The project lasted over two years from 2021 to 2023, including the continuous monitoring of the two bridges over 18 months.

1. Theoretical background

1.1 Fatigue assessment

Fatigue is the phenomenon by which microscopic damages inside a building material like iron or steel slowly expand through time, until they gather into cracks and may induce a brittle failure. The initiation phase of fatigue, when the damages remain invisible, can last several decades or centuries and is described by the Wöhler theory, which links the fatigue to repeated load cycles on the material [5].

In today’s engineering practice, the fatigue is considered for the design of bridges according to norms, like the Eurocode 3 part 1-9 in Europe. These norms qualify the resistance to fatigue by a detail category, expressed in MPa, which is the value of the stress cycle range that the structure can resist two million times in its lifetime. This number of cycles varies according to Wöhler’s curve depending on the actual stress cycle ranges. Methods like the rainflow counting in combination with Palmgren-Miner’s rule are used to deduce a fatigue lifetime from spectra of numerous cycles of varied ranges [6].

This study relies on these fundamental ingredients. In addition, a probabilistic approach of the damage accumulation through time and the related survival probability of the structure is introduced.

1.2 Probabilistic methodology

The method for probabilistic fatigue analysis proposed for this study is described in detail by [3] and [4]. This approach takes into account uncertainty originating from two different sources: the presence of randomly distributed flaws in the structure, and the variability of the loading to which the structure is subjected.

The first source of uncertainty is addressed by considering each monitored point as an independent specimen undergoing cyclic loading with variable amplitude. In Wöhler’s theory, the fatigue life of a specimen subjected to cyclic loading with constant severity S , expressed in MPa, is observed to display statistical dispersion, so that Wöhler’s curve

actually represents a given quantile, corresponding to the survival probability $1 - p$, of the true random lifetime of the specimen. Assuming a Weibull model (with modulus $m > 0$) for the underlying statistical distribution, the first main result of [3,4] is the expression of the survival probability of the structure after n loading cycles as $P(n) = (1 - p)^{\sum_{k=1}^K [D_n^k]^m}$, where K is the number of monitored points and $D_n^k \in [0,1]$ is the cumulative damage computed at the k -th monitored point after n cycles.

The second source of uncertainty comes from the observed cumulative damage D_n^k , which is considered to be the sum of independent random variables describing the cumulative damage increment at each cycle. In the regime of a large number of cycles, the law of large numbers allows to approximate this random quantity by the deterministic number $nD^{eq,k}$ (where $D^{eq,k}$ is the equivalent deterministic damage at the point k), which can be directly estimated from measurements and encodes the relevant features of the distribution of the loading cycles. This yields the formula $P(n) = (1 - p)^{\sum_{k=1}^K [nD_n^{eq,k}]^m}$ for the survival probability of the structure, taking into account both sources of randomness.

This formula is analytic and can be easily evaluated. In particular, the quantile N_p for a survival probability $1 - p$ of the fatigue lifetime of the structure is given by the formula $\frac{1}{(N_p)^m} = \sum_{k=1}^K \frac{1}{(N_p^k)^m}$, where N_p^k is the deterministic fatigue lifetime predicted by the Palmgren-Miner rule for each monitored point. Importantly, N_p is smaller than $\min_{k=1, \dots, K} N_p^k$, hence using the latter quantity leads to a systematic overestimation of the structure's lifetime. The use of the probabilistic approach allows to avoid this overestimation and therefore improves the safety of the fatigue lifetime assessment.

2. Implementation on the Loire iron truss bridges

2.1 Description of the bridges

The Haut-Village and the Mauves bridges are two historical iron truss bridges spanning the Loire River upstream the city of Nantes, in western France (Fig. 1). Both were built in 1882 for light local traffic of horse-drawn carts, and now support modern road traffic. They have a very similar design: a single box girder made of iron truss, with main spans of 45 m in length. The piers are made of masonry founded on timber piles in the riverbed. The Haut-Village bridge is 225 m long with five spans, and the Mauves bridge is 482 m long with eleven spans.



Fig. 1. Haut-Village Bridge (left) and Mauves Bridge (right).

2.2 SHM system

Numerous sensors have been installed on both bridges in the frame of the GeRICO project, for different purposes beyond fatigue analysis, like weigh-in-motion [7], operational modal analysis, and model updating [8]. They include many optical strands for strain measurement, accelerometers for vibration assessment and some extensometers. We only focus here on the optical strands used for the fatigue analysis: 32 sensors on the Haut-Village bridge and 18 on the Mauves bridge.

The set of optical strands strain sensors is designed to cover most of the “hot points” for the fatigue analysis, at least on a sample of a few spans on each bridge. They include longitudinal sensors on the upper and lower flange at mid-span for the strongest bending effects, along with diagonal shear strain sensors near one of the piers in the case of the Mauves bridge. The optical strands are strain sensors using the principle of light attenuation in braided fiber optics to measure the average strain over a length basis of one meter, thus smoothing the effects of material heterogeneity and giving a strain value relevant at the scale of the bridge deck [9].

Figure 2 displays the sensor setup for the example of the Mauves bridge, on two consecutive spans (“T6” and “T7”). The setup for the Haut-Village bridge is similar, but without shear strain sensors and with four spans monitored for the bending effects instead of two. There are also six additional optical strands on the Haut-Village bridge set on transverse beams.

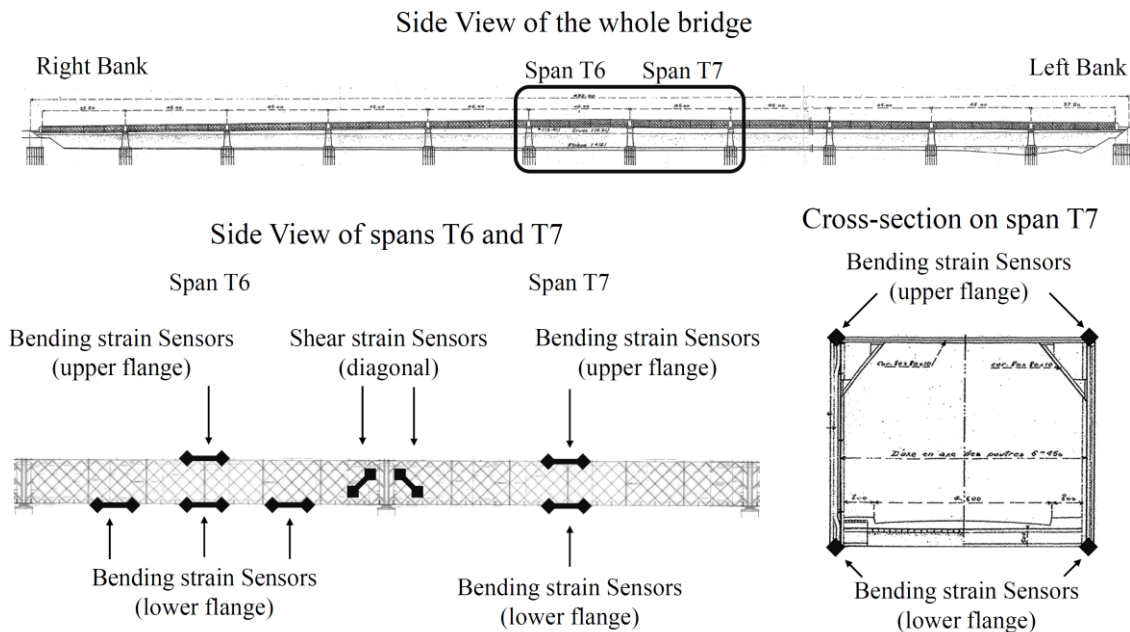


Fig. 2. Layout of the sensors of the monitoring system on the Mauves bridge.

2.3 Strain data available for fatigue analysis

The strain data was recorded for 18 months according to a threshold trigger: each time the variation of the strain within a four-seconds rolling window exceeds a preset threshold value, a dynamic record at a sampling rate of 100 Hz is triggered, the duration of which is of around 30 seconds. The recording stops five seconds after the trigger condition is not fulfilled again. Thus, the data is a collection of numerous records, each of them corresponding to the passage of one vehicle on the bridge, heavy enough to trigger the threshold, with about 140 items every day (70,000 in total) for the Haut-Village and 100 items every day (50,000 in total) for

the Mauves bridge. For each record, we have synchronized data on all the sensors for each bridge.

Once the strain data has been recorded, it is prepared for the fatigue analysis according to steps as follows:

- The strain cycles of each record for each sensor are counted and classified by range according to the rainflow cycle counting method. Cycles with a very low range below 0.005 mm/m are erased.
- For each sensor, a table is built with all the cycles of each day (one column per day) featuring the number of cycles of all the records of the day classified into range bins (one line for a 0.001 mm/m wide bin).

Figure 3 displays a visualization of such a table on the example of one bending strain sensor of the Haut-Village bridge. The colour scale reflects the number of cycles. A few unusual traffic loads are pointed out as high-range cycles. To enhance the readability of the chart, the period of each column is one week instead of one day.

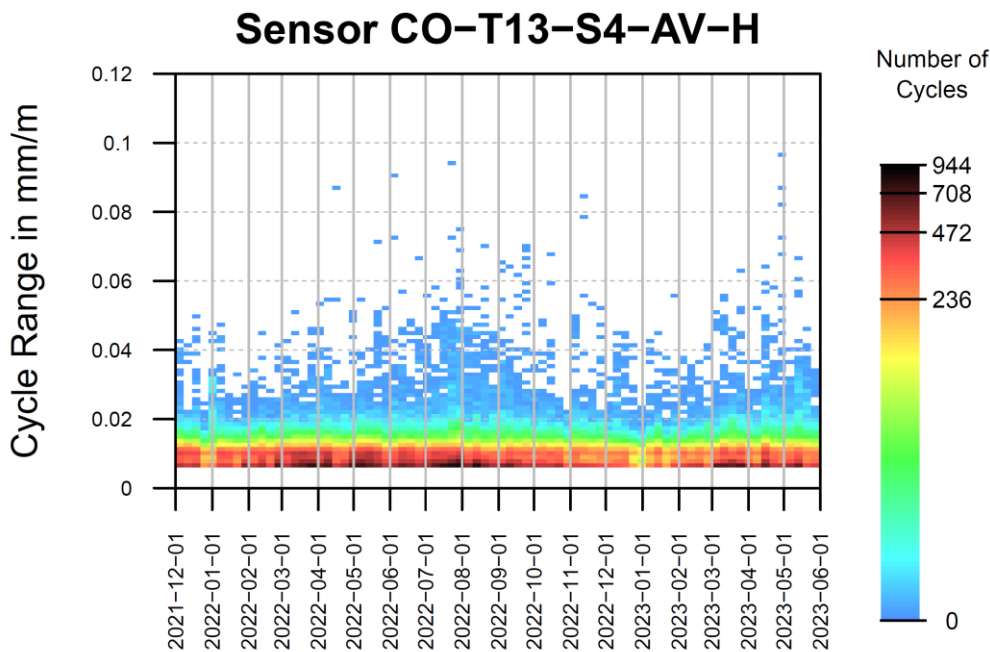


Fig. 3. Weekly strain cycle table for the 18 months of monitoring on one sensor of the Haut-Village bridge.

3. Probabilistic fatigue analysis results

The study presented in this contribution is an exercise to test the new probabilistic method for fatigue analysis. It does not claim to give a definitive fatigue assessment for the case of the two bridges, even if the orders of magnitude of the results are still relevant, under the set of assumptions described below.

3.1 Description of the scenarios

Three different analysis scenarios are tested for each bridge. The aim of this exercise is to compare and discuss the results in terms of fatigue lifetime, for different cases depending on the number of sensors involved. Indeed, one main issue of the probabilistic method is to consider the right number of sensors into the analysis, to ensure that the fatigue risk of every “hot spot” is well considered.

Table 1 explains the different scenarios tested. The first one is a “naïve” approach in which all the sensors, and only them, are considered. In the second scenario, the study is limited to the sensors associated with bending effects: thus, it is not valid for any fatigue phenomenon which may occur anywhere on the bridge, but for fatigue due to the bending of the monitored spans only. In the third scenario, starting from the second one, some sensors are duplicated to reach a virtual situation in which every span of each bridge would have been monitored, assuming that the actual sample of monitored spans is representative enough to justify the duplication (the uncertainty related to this duplication is not studied here).

Table 1. Scenarios for fatigue analysis.

Bridge and Scenario	Number of sensors	Duplicated sensors	Number of spans
Haut-Village, scenario 1	32	0	4
Haut-Village, scenario 2	12	0	4
Haut-Village, scenario 3	20	8	5
Mauves, scenario 1	18	0	2
Mauves, scenario 2	8	0	2
Mauves, scenario 3	44	36	11

The comparison of the scenarios is interesting because of the similarity of the two bridges, yet with a strong difference in terms of sampling: for the Haut-Village, the virtual situation with a comprehensive monitoring is only a marginal completion compared to the real situation, whereas the case of the Mauves bridge requires a massive duplication to simulate the comprehensive monitoring.

To allow a comparison on a similar basis, the other assumptions related to fatigue are set at the same value for all sensors and all scenarios. In particular, the Young modulus is set at 210 GPa, and the detail category is set at 36 MPa, which is a very conservative value, the lowest possible according to Eurocode 3. It is strongly reminded that these values are chosen for the purpose of this test exercise only. They may not reflect the real characteristics and fatigue resistance of the bridge on field. Moreover, the results presented below shall be considered as conservative.

3.2 Results for each bridge and scenario

The fatigue analysis is performed for each scenario according to the method described at §1.2. The fatigue lifetime is set for a survival probability of 95%. Figure 4 gives one example of survival probability curves for one scenario: the plain line is the global curve for all the sensor locations, whereas curves for each sensor are displayed as dashed lines.

The summary of the results for the six scenarios is presented in table 2. The value of the fatigue lifetime is estimated according to the conservative assumptions chosen.

Table 2. Probabilistic fatigue analysis results. All values in years.

Bridge and Scenario	Fatigue lifetime (95% survival)	Minimum lifetime for one sensor	Maximum lifetime for one sensor
Haut-Village, scenario 1	396	951	> 10,000
Haut-Village, scenario 2	475	951	> 10,000
Haut-Village, scenario 3	257	951	> 10,000
Mauves, scenario 1	399	1345	7809
Mauves, scenario 2	567	1345	7472
Mauves, scenario 3	183	1345	7472

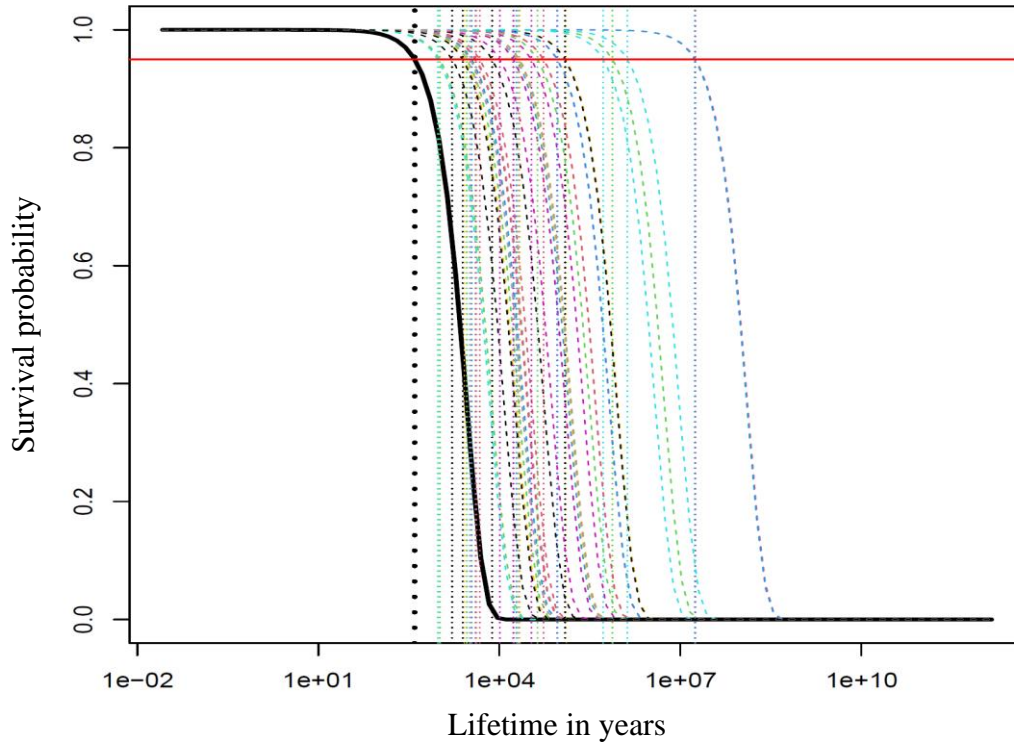


Fig. 4. Survival probability curves for the scenario 1 on the Haut-Village bridge.

4. Discussion and conclusion

The results show relevant orders of magnitude for a fatigue lifetime estimation under the conservative assumptions considered here, with a value of 257 years for Haut-Village and 183 years for Mauves in the worst scenario. In both cases, the sensor with the lowest individual lifetime estimation is one of the bending strain sensors, which justifies the choice to consider the bending effect as a comparison basis and to switch from scenario 1 to scenario 2 then 3.

A first significant result is the difference between the minimum lifetime for an individual sensor (the “weakest point”) and the global lifetime estimated through the probabilistic approach, the last being from two times (Haut-Village) to more than seven times lower (Mauves). This emphasizes the necessity to consider the uncertainty margin at the global scale of the structure rather than a deterministic “weakest point” approach, which may lead to optimistic overestimations.

The second result is the incidence of the sensor duplication to virtually cover the whole bridge. In the case of Haut-Village, we show that even a marginal completion with 8 sensors out of 20 has a significant effect, with an estimation decreasing from 475 years to 257 years. In the case of Mauves, the massive duplication of 36 sensors out of 44 reduces the estimation by a factor three, from 567 years to 183 years. This result appears logical, as the fatigue risk for any of the non-monitored spans needs to be considered, thus increasing the probability of failure of the whole bridge in related proportions.

This study shows the applicability of the probabilistic method for fatigue analysis on metallic truss bridges. Even under conservative assumptions, the estimated fatigue lifetime has an order of magnitude of about two centuries. A main finding is the necessity of a virtual extension of the available strain measurements to non-monitored parts of the bridge, to avoid an optimistic overestimation of the lifetime. In the probabilistic approach, all “hot points” of the structure must be considered to estimate the uncertainty on the survival probability, even

if they are not monitored. The simplified way proposed here is to duplicate the data of sensors set on similar locations.

Further improvements might be studied in the future. For example, the lifetime is estimated according to the assumption that the recorded strain cycles due to the traffic loads are representative of the whole life of the bridge, which obviously is conservative, as traffic loads have become heavier since the end of the 19th century. Thus, a refined extension of the strain cycle ranges to the past and future, assuming the non-stationarity of their distribution, would be an interesting topic for next studies.

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