

**Jan KREJSA<sup>1</sup>, Miroslav SÝKORA<sup>2</sup>****EFFECT OF THE LENGTH OF TRAFFIC FLOW RECORDS ON THE ESTIMATE  
OF A BRIDGE SERVICE LIFE****Abstract**

The service life of bridges is significantly affected by fatigue of used material induced by heavy vehicles. Therefore, precise determination of the vehicle weight is of crucial importance for the calculation of fatigue damage and the prediction of the bridge serviceability. This paper investigates accuracy of the determination of fatigue depending on the length of traffic flow recording. The presented data were obtained from the measurements carried out on a bridge of the Prague Highway Ring. The analysis reveals that the optimal length of traffic recording is about 30 days.

**Keywords**

Length of recording, fatigue, heavy traffic, traffic flow, Palmgren-Miner rule.

**1 INTRODUCTION**

The service life of a bridge depends on the effects of loadings imposed to the bridge. Eurocodes, the European standards for the design and assessment of structures, introduce limit states for verification of different types of structures. Fatigue limit state is one of them. This state may be a critical criterion for road and railway bridges. Generally, the fatigue damage is caused by cyclic loading and depends on frequency and stress magnitude of loading cycles. Fatigue damage relates to the structures exposed to considerable dynamic loading.

The paper is focused on the effect of the length of traffic flow recording on the accuracy of estimating road bridge service lifetimes, since the data about the traffic flow on the bridge can lead to economical savings. The traffic flow data have been obtained on a bridge of the Prague Highway Ring [1, 2].

**2 FATIGUE**

Load models for fatigue of road bridges are described in EN 1991-2 [3], Chapter 4.6. Five different load models for vehicles are introduced in this code, but the practical application of these models is not adequately described. In practice, the models FLM1, FLM2 and FLM3 (depending on the construction material of a bridge superstructure) are used due to their simplicity. However, these models are rather conservative [3] and the fatigue assessment may lead to overly conservative – non-economical design of structures.

**2.1 Data obtaining**

In the case of critical fatigue assessment, it is recommended to determine traffic intensities, which are provided by the Czech roads and highways authority ([www.rsd.cz](http://www.rsd.cz)). These data have to be

---

<sup>1</sup> Ing. Jan Krejsa, Department of Structural Reliability, Klokner Institute, CTU in Prague, Solinova 7, Prague 6, 166 08, Czech Republic, phone: (+420) 224 353 504, e-mail: [jan.krejsa@cvut.cz](mailto:jan.krejsa@cvut.cz).

<sup>2</sup> Assoc. Prof. Ing. Miroslav Sykora, Ph.D., Department of Structural Reliability, Klokner Institute, CTU in Prague, Solinova 7, Prague 6, 166 08, Czech Republic, phone: (+420) 224 353 850, e-mail: [miroslav.sykora@cvut.cz](mailto:miroslav.sykora@cvut.cz).

combined with vehicle weights, which can be obtained by dynamic measurements [4, 5]. The data from the dynamic measurements contain the real vehicle weights (structural response given in terms of the change of stress or deformation) and the real times when the vehicles passed.

## 2.2 Material properties – Wöhler curve

Augustin Wöhler (1850) created a theory of the fatigue failure of a material describing the relationship between the stress amplitude and the number of loading cycles. The dependence of these variables is called the Wöhler fatigue curve ( $S-N$  curve – see Fig. 1) [6].  $S-N$  curves are the most used tool for the assessment of fatigue service life.

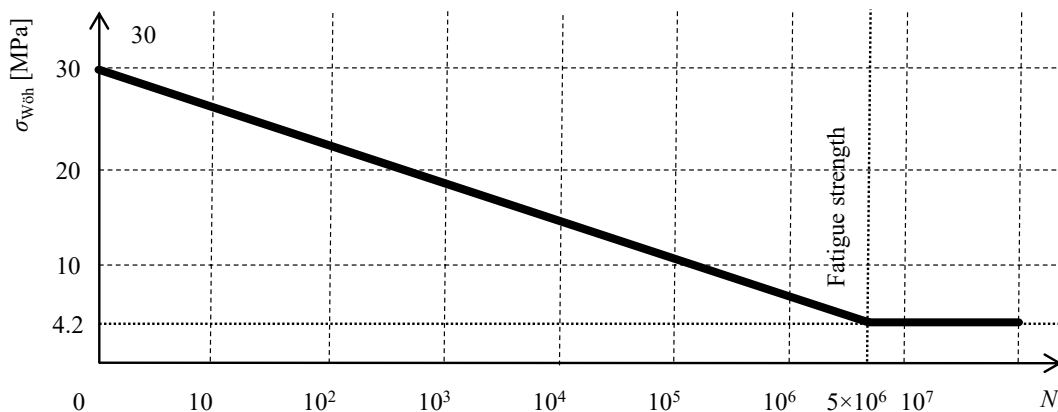


Fig. 1: Wöhler curve

For common construction materials, fatigue strength is known. It is normally related to a number of cycles in the range between  $10^6$  to  $10^7$  cycles (Fig. 1).

## 2.3 Palmgren-Miner rule of the cumulative damage

The Palmgren-Miner rule of the cumulative damage can be applied to account for different weights of heavy vehicles [7]:

$$D_{\text{fat}} = \sum(n_i/N_i) \quad (1)$$

where  $D_{\text{fat}}$  is the fatigue damage,  $n_i$  the number of recorded cycles and  $N_i$  the number of cycles from the Wöhler curve. Variables  $n_i$  and  $N_i$  depend on the response of the structure induced primarily by weights of vehicles passing the bridge.

## 3 DATA

The acquisition of the measurements was supported by the grant of the Ministry of Transport of the Czech Republic (2004 – 2007, “Response of the bridges on the thermal and transport loading”) that was focused on the deformation of a bridge caused by temperature changes and vehicles weight. The data were obtained from the bridge of the Prague Highway Ring using the measurement station EMS DV 803, 14 sensors of relative deformation (tensometers) and 4 sensors of acceleration (accelerometers).

Filtered data (without the effect of temperature changes) provided by Prof. Ing. Michal Polak, CSc. contained the number of vehicles per day divided into 32 weight categories:

- One category 0 to 10 tons
- 30 categories in the range from 10 to 85 tons, with the difference of 2.5 ton between categories
- One category for the range from 85 to 200 tons.

The measurement database contains daily records made from 1.1.2008 to 21.1.2010 with the total number of 628 days. The total number of vehicles that passed the bridge during the measured time is over 1.8 million. Illustration of the measurement database is in Tab. 1.

Tab. 1: Illustration of the measurement database

Date	Day	0 – 10 t	10 – 12.5 t	12.5 – 15 t	15 – 17.5 t	17.5 – 20 t	20 – 22.5 t	22.5 – 25 t	25 – 27.5 t	27.5 – 30 t
1.1.2008	2	0	1	31	41	29	20	22	9	8
3.1.2008	4	0	8	181	438	307	246	161	153	124
4.1.2008	5	0	5	214	464	391	304	211	182	153
5.1.2008	6	5	12	83	215	171	147	156	135	124
6.1.2008	7	34	60	149	241	176	131	93	89	80

#### 4 PROCEDURE FOR DATA ANALYSIS

The main goal of this study is the statistical evaluation of the length of traffic flow recording that is not related to the assessment of a particular bridge. Therefore, the assessment is based on Wöhler curve for a generic material and stress amplitudes caused by the real traffic spectrum. The material properties and stress amplitude are chosen so that the resulting value of cumulative damage obtained by the Palmgren-Miner rule is approximately unity during the service life of 100 years. The calculation procedure can be summarised in the following steps:

1. Development of sub-databases for different record lengths (1, 7, 30 and 120 days)
2. Determination of the average numbers of vehicles per different lengths of record for each weight category
3. Prediction of numbers of vehicles  $n_i$  for each weight category considering a service life of 100 years, i.e. by extrapolation of the average number of vehicles given a particular length of record
4. Specification of the Wöhler curve (Fig. 1):

$$\begin{aligned}\sigma_{Wöh} &= 30 \text{ MPa} - 3.85 \log N; \quad \text{for } 1 \leq N \leq 5 \times 10^6 \\ \sigma_{Wöh} &= 4.2 \text{ MPa}; \quad \text{for } N > 5 \times 10^6\end{aligned}\quad (2)$$

5. Estimation of the stress amplitude  $\Delta\sigma_{i,\text{real}}$  for representative vehicles in each weight category.
6. Estimation of the maximum number of vehicles  $N_i$  for each weight category according to the Wöhler curve (weight categories for which  $\Delta\sigma_{i,\text{real}} \leq 4.2 \text{ MPa}$  are eliminated):

$$N_i = 10 \exp[(30 \text{ MPa} - \Delta\sigma_{i,\text{real}}) / 3.85] \quad (3)$$

7. Assessment of the cumulative damage by Palmgren-Miner rule  $D_{\text{fat}}$  (equation (1)) for different lengths of record
8. Statistical evaluation of  $D_{\text{fat}}$  for different lengths of record:

- evaluation of the mean value  $m_{D_{\text{fat}}}$ , of the coefficient of variation  $v_{D_{\text{fat}}}$  and the skewness  $w_{D_{\text{fat}}}$  for the service life time  $t_{\text{zb}}$  (only the mean  $m_{D_{\text{fat}}}$  depends on  $t_{\text{zb}}$ )
- estimation of three-parametric lognormal distribution for  $D_{\text{fat}}$  [8]
- assessment of the probability of failure  $p_f(t_{\text{zb}})$  associated with the service life by using the cumulative distribution function of  $D_{\text{fat}}$ :

$$p_f(t_{\text{zb}}) = P[D_{\text{fat}}(t_{\text{zb}}) > 1] \quad (4)$$

- assessment of the reliability index  $\beta$  – see EN 1990:2011 and its dependence on  $t_{zb}$ :

$$\beta(t_{zb}) = -\Phi^{-1}[p_f(t_{zb})] \quad (5)$$

where  $-\Phi^{-1}$  is the negative value of inverse function of general normal distribution.

## 5 DATA ANALYSIS

All recorded data are extrapolated in accordance with the procedure described in Chapter 4. The results of the statistical evaluation of fatigue damage for different lengths of record are reported in Tab. 2. Fig. 2 shows the influence of the length of record on the coefficient of variation of cumulative damage according to the Palmgren-Miner rule.

Tab.2: Statistical evaluation of fatigue damage for different lengths of record

Length of record	Number of assessments	Total number of days	Total number of vehicles	$D_{fat}$		
				$m_{Dfat}$	$v_{Dfat}$	$w_{Dfat}$
Extrapolation from all data	1	628	1864886	1.019	-	-
1 day	628	628	1864886	1.019	1.399	2.701
7 days	89	623	1852822	1.026	0.767	1.179
30 days	20	600	1818270	1.063	0.564	0.283
120 days	5	600	1818270	1.063	0.511	0.722

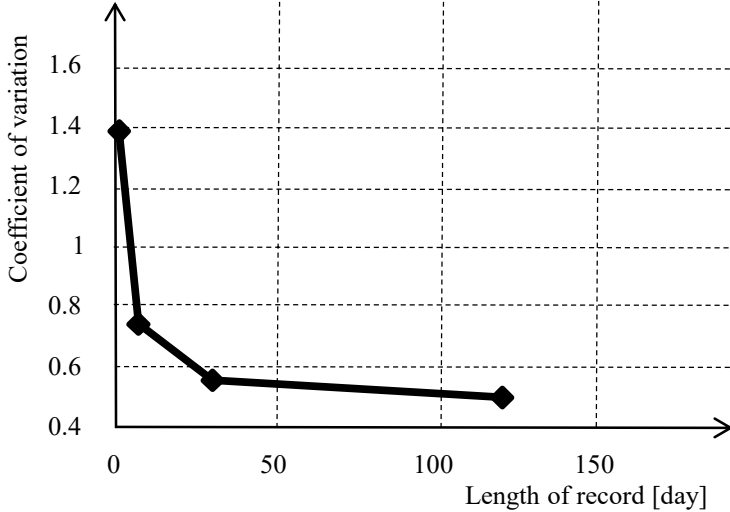


Fig. 2: Influence of the length of record on the coefficient of variation of cumulative damage by the Palmgren-Miner rule

Tab. 2 shows the assessment of different lengths of record and their influence on  $D_{fat}$  during the service life 100 years. Only complete periods with respect to the lengths of record are involved in the assessment. This causes differences in the total numbers of days and vehicles in Tab. 2.

Tab. 2 and Fig. 2 show that the increasing length of record significantly decreases with coefficient of variation while the mean value is nearly independent. When the length of record is 120 days, the coefficient of variation is three times lower than for the daily records.

The analysis is based on the assumption that the response of the structure is linearly dependent on vehicle weight. The analysis reveals that the number of cycles corresponding to the fatigue strength (Fig. 1) has the significant influence on the mean of  $D_{\text{fat}}$  (see Tab. 3). With an increasing number of cycles, the mean value of  $D_{\text{fat}}$  significantly increases and the fatigue damage can be affected even by light vehicles.

Tab.3: Influence of the number of cycles on the fatigue strength on the mean value of  $D_{\text{fat}}$

Number of cycles	Mean value of $D_{\text{fat}}$
$10^6$	0.46
$5 \times 10^6$	1.02
$10^7$	6.09

## 6 ESTIMATE OF SERVICE LIFE

Recorded data for fatigue assessment are described by the three-parametric lognormal distribution. Distribution depend on the service life  $t_{\text{zb}}$  is based on  $m_{D_{\text{fat}}}(t_{\text{zb}})$ ,  $v_{D_{\text{fat}}}(t_{\text{zb}})$  and  $w_{D_{\text{fat}}}(t_{\text{zb}})$ . It is necessary to note that only the mean value is affected by the service life. Probability of failure  $p_{\text{f}}(t_{\text{zb}})$  and reliability index  $\beta(t_{\text{zb}})$  are then assessed for different lengths of record (Fig. 3).

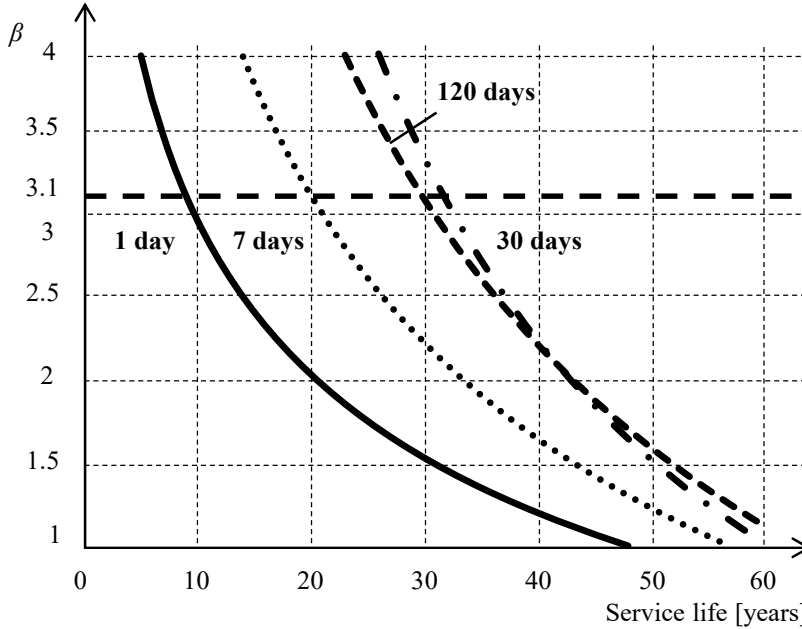


Fig. 3: Influence of the service life on the reliability index  $\beta$  for different lengths of record

Fig. 3 shows that for the target value of fatigue reliability index  $\beta_{\text{fat}} = 3.1$  the optimal length of record is 30 days (service life is more than three times longer than in the case of the length of record 1 day) [9]. Increasing length of record does not lead to more accurate estimates of the service life. In shorter records the influence of statistical uncertainty increases and the accuracy of the service life estimate decreases.

Strength uncertainties (related to the Wöhler curve and the Palmgren-Miner rule) and uncertainties caused by the measurement are neglected in the assessment. Changes in the traffic flow intensity are not considered; i.e. stationary conditions and ergodicity [10] are assumed. Dynamic effects, if they are not included in records as is the case of this study, are to be considered in a method of the assessment of fatigue based on observation.

## 7 CONCLUSIONS

The paper investigates the influence of the length of traffic flow records on the predicted fatigue service life of a road bridge. The traffic flow analysis reveals that:

- With an increasing length of record, coefficient of variation of fatigue damage significantly decreases while the mean value changes insignificantly.
- With an increasing number of cycles related to the fatigue strength (Fig. 1), the mean value of fatigue damage increases and the fatigue damage can be affected even by light vehicles.
- Optimal length of record is 30 days.
- Longer lengths of record do not lead to more accurate estimates of the service life. The influence of statistical uncertainty is larger for shorter records and the accuracy of the service life estimate is decreasing.

Within further studies, a more detailed analysis of traffic flow and an assessment of uncertainties considering the material strength properties (the Wöhler curve and the Palmgren-Miner rule) will be conducted.

## ACKNOWLEDGMENT

The study is a part of the students research project SGS16/195/OHK1/2T/31 supported by the SGS of CTU in Prague. Results of the project supported by the Czech Science Foundation under Grant P105/12/G059 have been utilised. Support of Prof. Michal Polak who kindly provided the data is appreciated.

## LITERATURE

- [1] POLAK, M., PLACHY, T. a ROTTER, T. Vibration Monitoring of the Bridge Loaded by Heavy Vehicle Traffic. In: *proceedings of the 5th wseas international conference on applied and theoretical mechanics (mechanics '09)*. Puerto de la Cruz, SPAIN, 2009, p. 120-123, Book Series: Mathematics and Computers in Science and Engineering. ISBN 978-960-474-140-3.
- [2] POLAK, M., PLACHY, T. a ROTTER, T. Long-time monitoring of the bridge response caused by heavy traffic and temperature changes. In: *proceedings of the 49th International Scientific Conference on Experimental Stress Analysis*. Brno, 2011, s. 341-348, ISBN 978-802144275-7.
- [3] EN 1991-2: Zatížení konstrukcí - Část 2: Zatížení mostů dopravou, Praha: ÚNMZ, 2005.
- [4] MORALES-NÁPOLES, O., STEENBERGEN, R.D.J.M., Analysis of axle and vehicle load properties through Bayesian Networks based on Weigh-in-Motion data, *Reliability Engineering & System Safety*, Volume 125, May 2014, Pages 153-164, ISSN 0951-8320, <http://dx.doi.org/10.1016/j.ress.2014.01.018>.
- [5] FEYPELL DE LA BEAUMELLE, J.B., V.Improving truck safety: potential of weigh-in-motion technology. *IATSS Res* 2010; 34(1): 9–15.
- [6] EN 1993-1-9: Design of steel structures - Part 1-9: Fatigue, Praha: ÚNMZ, 2006.
- [7] EN 1992-2: Design of concrete structures - Part 2: Concrete bridges - Design and detailing rules, Praha: ÚNMZ, 2007.
- [8] HOLICKY M. Introduction to Probability and Statistics for Engineers, Heidelberg: Springer, 2013
- [9] fib 2013. fib Model Code for Concrete Structures 2010. Lausanne: fib.
- [10] MELCHERS, R.E., Structural Reliability, Analysis and Prediction. John Wiley & Sons, 2002.