# Methods for Better Assessment of Fatigue and Deterioration in Bridges and Other Steel or Concrete Constructions

J. Menčík, B. Culek, Jr., L. Beran, and J. Mareš



***Abstract*—**Large metal and concrete structures suffer by various kinds of deterioration, and accurate prediction of the remaining life is important. This paper informs about two methods for its assessment. One method, suitable for steel bridges and other constructions exposed to fatigue, monitors the loads and damage accumulation using information systems for the operation and the finite element model of the construction. In addition to the operation load, the dead weight of the construction and thermal stresses can be included into the model.

The second method is suitable for concrete bridges and other structures, which suffer by carbonatation and other degradation processes, driven by diffusion. The diffusion constant, important for the prediction of future development, can be determined from the depth-profile of pH, obtained by pH measurement at various depths. Comparison with measurements on real objects illustrates the suitability of both methods.

***Keywords*—**Bridges, carbonatation, concrete, diagnostics, fatigue, life prediction, monitoring, railway, simulation, structures.

## I. Introduction

METAL and concrete structures often suffer by various kinds of deterioration. An accurate prediction of its rate during a long period and of the remaining life is difficult. In this paper, two methods are described, which have been developed at the Jan Perner Transport Faculty of the University of Pardubice: 1) computer–supported monitoring of load effects and fatigue in railway metal bridges, and 2) method for the condition evaluation of concrete structures.

Periodically loaded metal constructions suffer by fatigue. For its assessment, the load history must be known. However, only in some cases this can be predicted for a long period. More accurate information can be obtained by monitoring the loads and stresses, using, e.g., strain gauges. The paper describes an alternative approach, based on computer simulation: the stresses in a structure are calculated by the finite element method, with the information about the loads provided by the information systems monitoring the operation.

A critical issue in reinforced-concrete structures is the corrosion of steel reinforcement. The basicity of concrete protects the steel. However, due to carbonatation or other processes, the chemical composition of concrete changes and its pH degree decreases. If it drops below 9, the steel can start corroding. It is important to know when this happens. For diffusion-driven processes, the pH-degree at some time and depth may be described by formulae based on Fick´s law. The diffusion constant, important for the prediction of development, can be calculated from the depth-profile of pH, obtained by its measurement at various depths. In the following two sections, both methods are explained in detail.

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## II. Assessment of Fatigue in Large Metal Constructions

### A. Introduction

Metal bridges and other long-life structures, exposed to periodic load, suffer by fatigue. There are methods for fatigue assessment and for the prediction of remaining time to failure, provided the loads and the corresponding stress spectrum are known. Unfortunately, in many cases the loads for the whole life span cannot be predicted accurately as early as in the design stage. For example, bridges are designed for eighty years or more. During tens of years, new technologies can emerge and also the life of society can change significantly. For bridges this may bring changes in traffic density and axle loads. More accurate information can be obtained by monitoring the loads and stresses in important parts of the structure. This is possible using strain gauges fixed to the structure. However, permanent monitoring lasting years needs that the strain gauges and all components in the measuring chain have very high reliability and long life, and must be protected sufficiently against weather and mechanical damage, including intentional one. An alternative approach, suitable for railway bridges and some other structures, is based on computer technologies. In this section, the principle of the assessment of residual life will be explained first, and then the possibility of the determination of loads and stresses using traffic information systems and computer simulation.

*B. Assessment of Fatigue Effects and Remaining Life*

Two approaches are common in fatigue analysis of metal structures: 1) Woehler curve plus damage accumulation concept, or 2) fracture mechanics approach (for bodies containing cracks). For structures with high demands on safety, such as bridges, large cracks are unacceptable. Thus, the usable time of operation ends with the appearance of a measurable crack, and is assessed using Woehler curve, which relates the stress range $\Delta\sigma$ and the number $N_f$ of cycles to failure. There are various forms of Woehler curve, the simplest being

$$N_f = A\,\Delta\sigma^{-m} \quad , \tag{1}$$

with constants $A$, $m$. As the repeated loading of bridges is variable, a damage accumulation concept must be used. The most common one is the Palmgren-Miner linear rule, which defines the relative damage $D$ as

$$D = \Sigma(N_i / N_{fi}) \quad , \tag{2}$$

where $N_i$ is the number of loading cycles for $i$-th stress range, and $N_{fi}$ is the number of cycles to failure for this range; $\Sigma$ means summation for all $i$ = 1 to $n$ stress ranges. The failure is expected if $D$ = 1. Expressing $N_{fi}$ from the Woehler curve, Equation (2) can be rewritten as

$$D = \Sigma(N_i\,\Delta\sigma_i^{\,m}) / A \ . \tag{3}$$

The fatigue effects of randomly varying stresses can be assessed in several ways. Most often, the stress ranges $\Delta\sigma$ between various reversals are sorted and counted using the rain-flow method. As not only the stress range, but also the mean value of stress between two reversals, $\sigma_m$, plays a role, usually two-parameter rain-flow method is used, with $\Delta\sigma_i$ and $\sigma_{mi}$ as parameters. The mean stress in individual loading cycles consists of the mean stress, caused by train passage, and the stress caused by the dead weight of the bridge. If the temperature is nonuniformly distributed in the construction, also the corresponding thermal stresses (and their variations) should be considered. Since (3) corresponds to symmetrical loading cycles, the effect of nonzero mean stresses is usually considered by replacing $\Delta\sigma$ by equivalent symmetrical stress range, calculated from both $\Delta\sigma_i$ and $\sigma_{mi}$.

Several variants of this approach exist, e.g. Woehler curve with different slopes for various stress ranges, or Cortan-Dolan hypothesis, which counts all stress ranges, in contrast to Palmgren-Miner hypothesis counting only those exceeding the fatigue limit.

The limit state, decisive for intervention (e.g. repair), need not necessarily correspond to $D$ = 1, but, for safety reasons, to some smaller value, for example 0.8. Denoting this value as the limit value $D_L$, one can determine the remaining life $D_r$ (in nondimensional form) as

$$D_r = D_L - \Sigma D_j \ ; \tag{4}$$

$\Sigma D_j$ (for $j$ = 1…$N$ loading events or blocks) expresses the effect of loading up to this instant.

If the damage in individual loading blocks has random character, it is possible to determine the failure probability, corresponding to some time $t$ of operation, i.e. the probability of $D_r(t) \leq 0$. The number of cycles to failure is also a random quantity, even under constant stress amplitude, due to the scatter of the regression constants $A$ and $m$ in the fatigue curve (1). When the damage is calculated in semiprobabilistic manner, a suitable quantile of $A$ is usually worked with, e.g. 5%, while the exponent $m$ is assumed constant. Fully probabilistic approach and simulation technique Monte Carlo allow one to respect the random variability of $A$ and $m$.

The remaining life of a railway bridge may be expressed by the number of passing trains. For this purpose, the best unit of damage is that caused by one train, $D_1$. This damage can be calculated from (3) for the stress ranges and numbers of loading cycles corresponding to the pertinent train. The remaining number of passages till the failure is then

$$N_r = D_r / D_1 \tag{5}$$

It must be respected that various trains cause different damage. One method for this purpose uses permanent monitoring of loads and stresses during operation, via strain gauges glued to the construction, or via traffic information systems and computer simulation (see later). In another approach, the damages caused by individual trains are calculated from the data obtained by bridge monitoring only for a limited time (e.g. 24 hours), and then used to construct a histogram of damages $D_j$. Inserting the average damage for $D_1$ into (5), the average number of trains till the limit state is obtained. The upper confidence limit $D_{1,U}$ gives the lower (conservative) confidence limit for the train number, $N_{r,L}$. More information can be obtained using the Monte Carlo simulation, based on the probability distribution of $D_j$ and $D_r$. In this way, a histogram of $N_r$ can be created, allowing one to calculate the number of trains corresponding to various probabilities of survival or vice versa.

The remaining life may also be expressed in other units, e.g. days if the damage caused by one-day traffic is inserted as $D_1$ into (5). A longer monitoring interval characterises the variability in damages more adequately. However, also the long-term changes in loading and other factors must be included into the models for lifetime prediction.

*C. Determination of Stresses in Bridges Using Traffic Information Systems and Computer Simulation*

Stresses in various parts of a structure can be calculated with sufficient accuracy using the finite element method, provided the loads are known. For railway bridges, the basic information about live load can today be obtained from rail information systems. Railway companies or administration of transport infrastructure store the data about the movement of all trains in the railway network. These data can provide information about the individual trains going over a particular bridge: the types of locomotives and the passenger and freight cars, and the weights of transported goods. After supplementing them with the weights and dimensions of individual cars, it is possible to create the virtual load scheme for the pertinent train. The application is shown in the next section. Similarly, monitoring of trucks (done, e.g., for toll purposes) could be used for the simulation-based stress analysis in road bridges.

Another advantage of the computer-simulation based systems is that they enable consideration of various effects, which cannot be revealed by direct measurement via strain gauges. For bridges this concerns especially the dead weight of the structure. Important for some structures, such as bridges, are also thermal stresses. Bridge structures are exposed to varying air temperature and sun radiation. The temperatures are distributed nonuniformly in the construction and cause thermal stresses here, which can reach several tens of MPa. As they vary during day and night, as well as during year periods, they may also significantly influence the fatigue life.

### *D. Experimental Part*

The use of information systems and computer simulation for the assessment of fatigue life of metal bridges was investigated at the Transport Faculty of the University of Pardubice. A special procedure for the determination of the time course of live load stresses in bridges from the data of railway information systems has been developed [1], consisting of three steps. First, the finite element model of the bridge is prepared. Then, the influence lines for stresses at the investigated point are created by static analysis. Finally, the train passage is simulated by moving the virtual load model along these influence lines. For this, a computer program was created, able to calculate the time course of stresses and to select the characteristic values according to the purpose of the analysis, e.g. the stress ranges for rain-flow fatigue analysis.

The proposed method was verified by comparing the calculated stresses with those measured by strain gauges. The comparison was done for two steel railway bridges: a truss bridge and a plate-girder bridge, both over the Labe (Elbe) river. The strain analysis was performed using the finite element code IDA Nexis, with truss and plate elements; the train load data were taken from the information system CEVIS of Czech Railways. The stresses were measured using strain gauges glued at various points of each structure (main girders, cross beams and stingers). The data were processed using a dynamic amplifier. The traffic was monitored 24 hours, with about 150 train passages over each bridge. Figure 1 shows the measured and calculated time course of stresses caused by one train passage. One can see very good agreement between the model and measurement. For the common train velocities, quasistatic model was sufficient though dynamic effects could also be considered. More details can be found in [1]. Further development will be necessary, but it is obvious that, in principle, the time course of stresses in bridge constructions can be determined with sufficient accuracy using the data about trains from railway information systems.

Effort has also been devoted to the investigation of the influence of the dead load and thermal stresses on the fatigue [2 – 4]. This analysis was done for a steel bridge over the

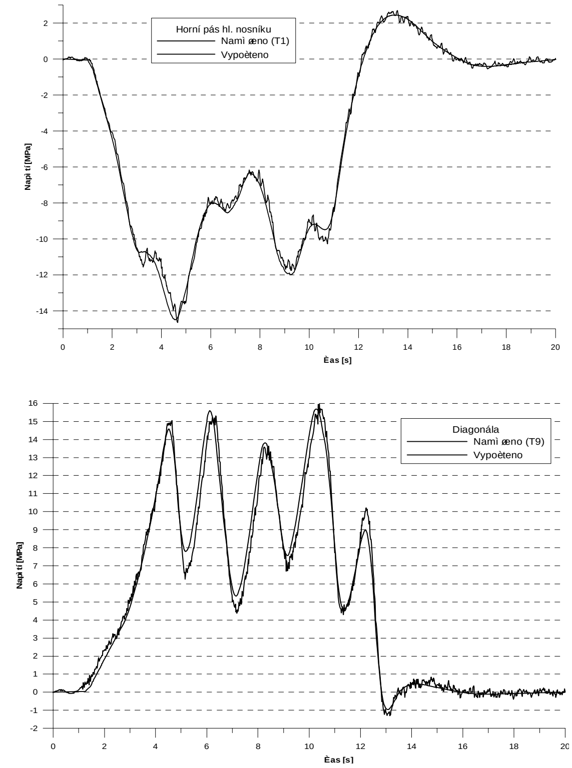


Fig. 1 Stresses caused by a passenger train – measured and calculated [15]. Upper graph – main girder, lower graph – diagonal truss. Horizontal axis: time [s], vertical axis: stress [MPa]. Curves with little undulations – measured data, smooth curves – calculated

Labe, in which a relatively large crack in a stinger near the conection with a cross girder was revealed after 32 years of operation. Two finite element models were created using ESA PT code. A simplified model of the whole bridge, made of one-dimensional and 2D elements, has provided the general distribution of forces in the construction. The second model served for obtaining a more accurate distribution of stresses in the critical region. This model contained more details, and the beams were modeled using 2D plate elements.

The stresses caused by traffic loads were obtained from strain gauges. The monitoring lasted 24 hours (with 177 train passages). The stresses from the dead weight of the bridge were calculated by the finite element method and added to those from traffic load. The thermal stresses were calculated by the finite element method also. The temperatures were determined using continuous records of air temperatures from a weather station, data from long-term monitoring the temperature of a piece of a massive steel (a rail), and one-day measurement done on the actual bridge. These data were used to find correction factors for the weather-station data used in finding the time course of bridge temperatures [3].

In order to get the calculated time to failure as close to reality as possible, the Woehler curve for the bridge material was determined by fatigue tests.

The damage accumulation was calculated using two-parameter rain flow method and Corten-Dolan hypothesis [2, 3]. The sufficient amount of data made possible the use of the probabilistic Monte Carlo simulation method for the prediction of the time to failure. As the purpose of this investigation was to find which factors should be considered and which could be neglected in the fatigue life prediction, the Monte Carlo simulations were done for three variants. The following table shows the times to failure in years (yr), calculated for various probabilities ($P_f$) of failing earlier; RF means rain-flow.

| | $P_f$ = 5% | 50% |
|---|---|---|
| 1–parametric RF without the influence of mean stresses and temperature: | 171.0 yr | 231.5 yr |
| 2–parametric RF without the influence of dead weight and temperature: | 42.0 yr | 57.0 yr |
| 2–parametric RF with the influence of dead weight and temperature: | 19.5 yr | 30.0 yr |

The actually observed time to failure was 32 years. One can see that the best prediction was obtained if two-parameter rain-flow sorting was used and if also the dead weight of the bridge and thermal stresses were considered. Neglecting these influences could lead to significant and dangerous errors.

## III. Assessment of Rate of Concrete Degradation

### A. Introduction

Large, long-life civil engineering structures, such as bridges, dams or cooling towers are made of concrete strengthened by steel bars. Structural steel is prone to corrosion, but concrete is alkaline, with high pH degree (12.6), and protects the steel. Due to environmental action, however, chemical composition of concrete changes and its pH decreases. The most common process is carbonatation: the basic concrete constituent, $Ca(OH)_2$, changes gradually due to the action of $CO_2$ from air to $CaCO_3$, with pH 7.0 (or 8.3 in saturated solution). When the pH-degree of concrete drops below 9, the steel reinforcement is no more protected and can corrode. This causes the reduction of its cross section area. Also, the rust has larger specific volume than steel, presses on the covering layer of concrete and can cause it to spall-off, leaving thus the steel bars unprotected, which can accelerate their corrosion. Also other substances can cause concrete deterioration with similar time course, e.g. sea water or chlorides from deicing salts.

Large concrete structures are expensive, and decisions about their repair or demolition must be based on a good knowledge of the actual condition of the concrete and prediction of its development. In this section, a diagnostic method is described, which can be useful especially for older structures. The proposed method is explained on carbonatation, but it may also be used for other diffusion-driven deterioration processes.

### B. Theoretical Part

Degradation processes in concrete usually proceed from its surface into the interior. The thickness $h$ of deteriorated layer grows approximately with the square root of time $t$,

$$h(t) = K\sqrt{t} \quad , \tag{6}$$

where $K$ is a constant, depending on the composition and density of the concrete and on the properties of environment (which can vary due to variations of temperature, air humidity and other factors). If $K$ is known, the depth of degradation or the time for reaching some depth can be calculated easily.

The constant $K$ must be determined experimentally. The easiest approach, but of limited accuracy, calculates it directly from the time $t$ elapsed since putting the object into operation, and from the measured depth $h$ of the unacceptable degree of carbonatation. Another approach measures the thickness of degraded layer in various times and fits the $h(t)$ values by (6). Unfortunately, this is very time consuming and impracticable for structures put into operation a long time ago. The third approach [5 – 7] uses the fact that the material properties in the surface layer of a body, exposed to a diffusion process, change (approximately) according to the formula

$$y(x,\, t) \;=\; y_S + (y_0 - y_S)\, erf\left(\frac{x}{2\sqrt{D\,t}}\right) \quad , \tag{7}$$

based on the Fick´s law for diffusion into semiinfinite body. In (7), $y(x, t)$ is the considered quantity, e.g. chemical composition, degree of pH or another property, $y_0$ is its initial value, assumed constant in the whole body, $y_S$ is the value of the surface, achievable by the process, $x$ is the depth below surface, $t$ is time, $D$ is the diffusion constant and erf($z$) is the error function. Formula (6) follows from (7) for $y$ = const. If the depth distribution $y(x, t_0)$ of the property $y$ at some instant $t_0$ is known, its fitting by (7) can yield the constants $D$, $y_0$ and $y_S$. Equation (7) then enables the determination of pH-degree for any depth and time, or the time when the property $y$ at some depth reaches certain value.

### C. Experimental Part

The proposed method was tested on a concrete block 18 years old [5]. A hole ∅18 mm was drilled and the dust was taken. The individual samples corresponded to the layers 0 – 10 mm, 10 – 20, 20 – 30, 30 – 40, 40 – 50 and 50 – 60 mm. The pH values degtermined (by electrochemical method) from the leached dust represented the average pH in each layer, so that they were inserted into (7) as the values for depths 5 –15 – 25 – 35 – 45 – 55 mm. The measured data were fitted by (7); the criterion was the minimum of squared differences between the measured and calculated values. The results were: $y_S$ = 7.986 and $y_0$ = 12.341 ($y$ stands for pH), and the diffusion constant for the assumed time of service $t$ = 18 years was $D$ = 8.199 $mm^2$/year. The coefficient of determination was $r^2$ = 0.985. This approximation is depicted by solid curve in Fig. 2.

The results are promising. Also further improvement might be possible. Equation (7) corresponds to the case when the property „$y$“ on the surface has been suddenly changed at time $t$ = 0 from $y_0$ to $y_S$ and kept constant. In reality, however, it is not this property, but the environment, which can be assumed „constant“. As diffusion is described by the same differential equation as non-steady heat transfer, one can use the known solution for temperature development in a semi-infinite solid, brought at time $t$ = 0 into contact with a fluid of a constant temperature [9]:

$$y(x,t) = y_S + (y_0 - y_S) \times \times \left[ erf\left(\frac{x}{2\sqrt{Dt}}\right) + \exp\left(Ax + Bt\right) erfc\left(\frac{x}{2\sqrt{Dt}} + \sqrt{Bt}\right)\right], \quad (8)$$

where erfc = 1 – erf. For carbonatation, $y(x, t)$ is the pH-value at depth $x$ and time $t$, $y_0$ is the original pH-value of the concrete, $y_S$ is its asymptotic value, and $A$, $B$ and $D$ are constants. All five constants can be determined by fitting the measured pH data by (8).

The six experimental values of $y(x, t')$, corresponding to $t'$ = 18 years, gave the following results: $y_S$ = 7.00, $y_0$ = 12.323, $D$ = 6.859 mm$^2$/year, $A$ = 0,000 mm$^{-1}$ and $B$ = 0.138 year$^{-1}$ (dotted cuve in Fig. 2). The coefficient of determination was $r^2$ = 0,991.

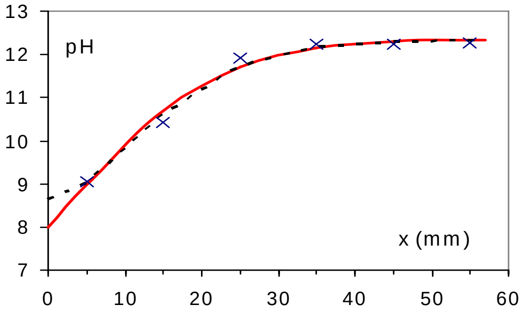


Fig. 2 pH degree at various depths (x) measured by electrochemical method [7]. Solid curve – approximation by equation (7), dotted curve – approximation by (8)

### *D. Discussion*

Curves (7) and (8) have similar character. However, equation (8) has five constants, so that more measured pH-values would be better. Actually, the direct fitting of the six measured pH-values by (8) has led to wrong values of some constants and to wrong shape of the curve outside the interval used for regression. This was corrected by introducing some constraints; the above constants were obtained for constraints $y_S \geq 7.0$ and $A \geq 0.0$ mm$^{-1}$. The pertinent curve (8), depicted by dotted line in Fig. 2, is close to function (7), with some difference only near the surface. This suggests one to use (7) for the characterisation of carbonatation and for the prediction of its further development, the advantage being that it has only three constants and thus needs less data points for the fitting. The approximations (7) or (8) can be suitable especially if the pH measurements are done relatively long time after putting the object into operation, so that the thickness of carbonated layer is not too small.

The experimental data show scatter, which should be included into the prediction of further deterioration. The simplest way uses the residual scatter of individual pH-values around the pH($x$) curve. As the degree of deterioration can also vary from a place to place, it can be recommended to use the data from several drilled holes, find the average curve and the residual scatter of all values around this curve. The confidence band for pH is then found by multiplying the square root of the residual scatter by a suitable constant.

## IV. Conclusion

Two methods for assessment of deterioration and remaining life of steel and concrete structures have been proposed. One method, suitable, e.g. for metal railway bridges, is based on computer simulation. The stresses in the construction are determined by the finite element method using the data on live load from the information systems monitoring the movement of trains in the railway network. The prediction of time to failure is more accurate if also the stresses caused by the dead weight and by varying temperatures are included into the calculations.

The other method, suitable for characterisation of concrete degradation, is based on the differential equation for diffusion and on the measurement of depth distribution of some property, e.g. the pH–degree. The method enables assessment of the long-term action of the environment, prediction of further development of carbonatation or other kind of degradation, e.g. due to chlorides, and the determination of the time till the structure reaches a defined degree of degradation. The method is especially suitable for older bridges and other concrete structures, where no regular measurements were done in the past.

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## References

[1] L. Beran, *Reliability and load carrying capacity of existing steel railway bridge structures.* PhD thesis. University of Pardubice, Pardubice, 2004.
[2] B. Culek, Jr., The complex lifetime evaluation of the steel bridge with member deck. *3rd Int. Conf. "Reliability, Safety and Diagnostics of Transport Structures and Means"*, Pardubice, 25–26. 9. 2008, University of Pardubice, 2008, pp. 33–40.
[3] B. Culek, Jr., et al., *Determination of influence of temperature on fatigue durability of steel bridges with member decks*. Tech. report. Annex to [8], University of Pardubice, 2007.
[4] B. Culek, Jr., B. Culek, Probabilistic assessment of the lifetime of the railway steel bridge across river Labe. *24th Danubia-Adria Symposium on Developments in Experimental Mechanics*. Sibiu, 19-22 September 2007. University Lucian Blaga, Sibiu, 2007, pp. 59 – 60.
[5] J. Mareš, *Diagnostics of atmospheric corrosion of concrete constructions in transport strucures.* PhD thesis, University of Pardubice, Pardubice, 2009.
[6] J. Mareš, J. Menčík, Experimental assessment of concrete deterioration in existing bridges. *3rd Int. Conf. "Reliability, Safety and Diagnostics of Transport Structures and Means"*. Pardubice, 25–26. 9. 2008, University of Pardubice, 2008, pp. 197–201.
[7] J. Menčík, J. Mareš, Characterisation and prediction of concrete deterioration in existing structures. *Int. Conf. „Life cycle assessment, optimisation, behaviour and properties of concrete and concrete structures*“, Brno, 12-14. 11.2008, FAST VUT Brno, pp. 218-223.
[8] J. Menčík, et al., *Determination of load carrying capacity and fatigue durability of bridge constructions*. Tech. reports (grant project GAČR 103/05/2066), University of Pardubice, 2005–2007.
[9] H. Gröber, S. Erk, U. Grigull, *Die Grundgesetze der Wärmeübertragung*. Springer Verlag, Berlin – Göttingen – Heidelberg, 1955.