

Assessment of Steel Bearing Structures - Estimation of the Remaining Fatigue Life

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Abstract. A significant number of steel bridges exist in operation worldwide. The budget for new infrastructure projects is tight, so the importance of inspection, maintenance and assessment of the existing bridges increases. A new fatigue assessment guideline for the estimation of the remaining fatigue life of steel bridges should be developed soon. This paper presents (i) a discussion based on the state-of-the-art review and (ii) new possibilities of applications of probabilistic methods for the time dependent reliability assessment of the lifetime of steel bridges. The probabilistic fatigue assessment procedure can be applied to existing steel bridges under cyclic loading. The guideline concentrates on the existing traffic infrastructure made from old steel due to its public importance. The essential general methods for these calculations are provided using structural and fracture mechanics and the reliability theory used in a probabilistic framework.

1. Introduction

The ever growing needs of society are characterized by significantly higher demands on the level of utilization of structures. During the lifetime of a structure big differences in its use, especially noticeable in older bridges, may occur. State-of-the-art reviews on fatigue life assessment of steel bridges are published, for e.g., in [1-5]. The advancement of computers has led to the development of computer modelling of fracture tests based on the finite element method [6-8] and probabilistic reliability assessment methods, which are based on statistical analysis [9-11], local [12-14] and global [15-18] sensitivity analysis and probabilistic analysis [19-20]. There has been a significant development in research into the relation between the behaviour and properties of materials and their structural characteristics [21-22]. Initial material and geometric imperfections are statistically evaluated in detail and their negative effects on the limit states are studied using finite element simulations [23]. Contemporary probabilistic approaches of reliability analysis [19, 20] can be applied with caution and minor modifications to assess the service life of older bridge structures [24-26]. High efficiency of the reliability assessment can be achieved by combining the abovementioned tools with modern techniques of MCDM [27-28].

In practice, the fundamental problems that need to be tackled include: the review of safety, serviceability and lifetime of load bearing engineering structures. Assessment of older steel bearing structures must be performed with regard to the duration of operation, which the structure is subjected to. The most significant changes in the loading of bridges occur during increase in the overall weight due to the axle loads of vehicles and the frequency of crossings, which leads to greater fatigue damage



than was foreseen in the design of the bridges. The most important fatigue parameters are the amplitude and frequency of loading. It is convenient to use the load model, which is based on weigh-in-motion (WIM) measurements, for the investigation of fatigue of bridges loaded with heavy trucks [29]. Other important parameters include the strength material characteristics of steel, which were monitored over a long period of time [30-32]. However, structures erected in the last century were designed based on other standards, without the use of computer technology and built using materials that are different from those used for present day structures. The material characteristics of bridges built between 1870 and 1940 are seldom available [33].

2. Fatigue limit state

The limit state function for fatigue in steel girder bridges can be expressed in terms of two variables:

$$N_F - N_n \geq 0 \quad (1)$$

, where N_F denotes the number of cycles to failure under the given stress history, and N_n denotes the number of applied load cycles. N_F and N_n are random variables and can be described using their probability density functions (pdfs). Pdf of N_F can be calculated for each structural member using linear fracture mechanics, provided that the pdf of the equivalent stress range was analyzed. This is possible if the histogram of stress range is known, which is usually not fulfilled. For a number of bridges the shape of the histogram of the stress range can be burdened with non-stochastic uncertainty, which can be described and analyzed using alternative methods of expressing uncertainty, for e.g. the application of fuzzy sets [24]. Uncertainty N_n can be considered as stochastic with mean value, which is equal to the presumed nominal value and variation coefficient 0.15 [34].

It may be noted that in equation (1) is analogous to the general function of limit state design, where it is assumed that the random static resistance R is, with probability P_f given in standard EN1990, greater than the random load effect, see e.g. [19, 20]. Generally, design according to EN1990, using the partial factors given in annex A1 and EN 1991 to EN 1999, is considered to lead to a structure with β value greater than 3.8 for 50 year reference period.

Structural reliability can be expressed using time-varying probability of failure. Analysis of the reliability of steel structures in time can be performed using methods like Thoft-Christensen and Baker [35] or Melchers [36]. Reliability is often analyzed using the reliability index β , which is considered to be a more illustrative variable than the failure probability [34].

$$\beta = \frac{\ln(\frac{m_{NF}}{m_{Nn}})}{\sqrt{v_{NF}^2 + v_{Nn}^2}} \quad (2)$$

, where m_{NF} is the mean value of cycles to fatigue failure, v_{NF} is the variation coefficient of cycles to fatigue failure, m_{Nn} is the mean value of the applied load cycles, v_{Nn} is the variation coefficient of the applied load cycles. Equation (2) is derived based on the assumption that $N_F = N_n$. Another prerequisite is that random variables N_F and N_n have lognormal pdf, which may not be fulfilled exactly for real bridges. Nevertheless, from a technical point of view, this assumption is acceptable when considering the number of additional factors, for which sufficient information is unavailable for their modelling and their effect on the life of the bridge is difficult to predict. The relationship between β and service years can be used to predict the remaining life of the bridge [25, 26].

3. Reliability analysis

Examples of time-dependent probabilistic reliability analysis based on (1) and (2) are listed in Table 1 and Table 2. The values of β in Table 1 were calculated considering the statistical characteristics of N_F as $m_{NF}=1E8$, $v_{NF}=0.5$ and present six variants of the calculation of time-varying reliability index β vs. time. The reliability index β decreases most rapidly in the first years of operation.

Table 1. Reliability index β vs. time for 6 variants of cycles per day

Year	300	500	700	900	1100	1300
	[cycles per day]					
1	13.06	12.08	11.44	10.95	10.57	10.25
2	11.73	10.75	10.11	9.63	9.24	8.92
5	9.98	9.00	8.35	7.87	7.49	7.17
10	8.65	7.67	7.02	6.54	6.16	5.84
20	7.32	6.34	5.70	5.22	4.83	4.51
30	6.54	5.56	4.92	4.44	4.05	3.73
40	5.99	5.01	4.37	3.89	3.50	3.18
50	5.56	4.59	3.94	3.46	3.08	2.76
60	5.22	4.24	3.59	3.11	2.73	2.41
70	4.92	3.94	3.30	2.82	2.43	2.11
80	4.66	3.69	3.04	2.56	2.18	1.86
90	4.44	3.46	2.82	2.33	1.95	1.63

Table 2. Reliability index β vs. time for 6 variants of m_{NF}

Year	1E7	2E7	4E7	6E7	8E7	10E7
	[m_{NF}]					
1	7.02	8.35	9.68	10.46	11.01	11.44
2	5.70	7.02	8.35	9.13	9.68	10.11
5	3.94	5.27	6.60	7.37	7.93	8.35
10	2.61	3.94	5.27	6.05	6.60	7.02
20	1.29	2.61	3.94	4.72	5.27	5.70
30	0.51	1.84	3.17	3.94	4.49	4.92
40	-	1.29	2.61	3.39	3.94	4.37
50	-	0.86	2.19	2.96	3.51	3.94
60	-	0.51	1.84	2.61	3.17	3.59
70	-	0.21	1.54	2.32	2.87	3.30
80	-	-	1.29	2.06	2.61	3.04
90	-	-	1.06	1.84	2.39	2.82

Table 2 assumes 700 cycles per day, $v_{NF} = 0.6$ and shows the values of β for six variants of m_{NF} . The relationship between β and years of service can be used to predict the remaining life of the bridge. Assessment is performed by comparing the attained reliability index with its recommended minimum value, which is determined by considering the consequences for loss of human life, and economic, social or environmental consequences [19]. Reliability index β usually has a target value of 3.8 provided that we consider the ultimate limit state for common design situations within the reference period of 50 years, see Table C2 in EN1990.

The assessment of existing bridges is mainly performed on the basis of results obtained from assessing hazards, load effects that can be anticipated in the future, material properties, geometry and the structural state of the bridge. Numerous changes in the stress state of load bearing steel members limit the lifetime of bridges. It is essential to integrate the results of fatigue studies and the remaining life into the planning of public transportation, which should adapt social, economic and demographic parameters to the current “health” of the bridge structure so that shut down of bridge is controlled and planned for a period that has minimal negative social and economic consequences. A typical example is Žďákov Bridge, which was in continuous operation from 1967 to 1998. In the late summer of 1998 a long vertical crack was found in the bridge decking during routine maintenance. Frost damage contributed significantly to the development of the crack. The bridge was then preventively closed to all traffic resulting in major traffic problems.

Traffic problems can be prevented in the case of failures that can be predicted and anticipated in the future. Fatigue is one of the critical forms of damage potentially occurring in steel bridges. Unfortunately, accurate assessment and prediction of the state of fatigue damage, as well as the remaining fatigue life of steel bridges remains a difficult and unsolved problem. At present the most commonly repaired bridges in the Czech Republic are those that were built in the 1960’s to the 1980’s. In addition to common failures, such bridges do not satisfy the requirements of current standards for the ultimate limit state, which results in the extent and method of reconstruction and repair. The basic tasks of engineers are to ensure longer life of bridges, safety during their operations and to reduce repair costs in future years. In view of the severity of the forms of failure and the importance of modes and mechanisms of failure of load bearing structures, fatigue is, unfortunately, still not regarded as one of the priority factors that should be taken into account in detail and with high diligence during the design of bridges. Probabilistic analysis of reliability and limit states can provide qualitatively new and highly relevant data for planning the shutting down of bridges, investment costs and workload.

4. Conclusions

The basic concept for assessing reliability of bridges in time was presented in this study and corresponding literature review pertinent to ensuring the reliability of load bearing steel structures, management and life cycle analysis was provided. Existing steel bridges represent a strategic part of infrastructural nets, which increasingly require accurate evidence-based analysis of their remaining life. The present study shows which input random variables are essential for monitoring the life of bridges. A general problem is the availability of statistical data on older bridges, for which regular measurement of the flow of vehicles or of axles was not performed and the propagation of fatigue cracks was not monitored, which could be useful in the statistical analysis of the limit states of steel load bearing elements. This study provides an overview of recent studies and research achievements in the field of reliability analysis and assessment of steel structures. It is necessary to pay increased attention to fatigue limit states of steel structures in time. It is also extremely important to understand the amount of work being carried out in the field of bridge assessment, which is a relatively new, rapidly growing aspect of bridge engineering science, since the amount of resources needed for the complete repair of existing bridges is significant for the owner or managing public authorities.

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