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Approximated methods of estimation of the reliability of framed railway structures of railway bridges

Приближенные методы оценки надежности балочных пролетных строений железнодорожных мостов

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Ключевые слова: отказ; надежность; интенсивность нагрузки; безотказная работа; высокоскоростное движение; технологический состав

Abstract. The development of methods for rapid assessment of the reliability of span structures of beam railroad bridges is relevant in connection with the trend towards increasing loads from the reversing freight rolling stock and the speeds of movement on the main transport with a mixed cargo-and-passenger turnover. This problem is especially urgent for the creation and implementation of special technical conditions (STC) for the design of bridges on high-speed lines (BCM), as in Europe and in America, the process of improving the regulatory framework is actively being implemented and innovative developments in this field. Normative documents of the STC take into account only two opposite tendencies. The first is the reduction of equivalent loads from specialized high-speed rolling stock, the second is the increase in dynamic coefficients with an increase in speeds of up to 350 ... 400 km/h. At the same time, the documents being developed require the provision of a relatively heavy load from a special technological rolling stock when planning work on the maintenance of the railway track, as well as during the elimination of the consequences of accidents and other emergencies. The class of this load corresponds to C11, which is 78.5 % of the load of class C14, which is calculated for bridges on public railways. The authors suggests a method for estimating the reliability of a limited pass on beam span

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structures of a railway transport, the load from which is 10–20 % higher than the design load. A solution describing the probability of failure-free operation in the absence of a sudden failure at the level of 0.97-0.98 is described. Such a solution is relevant for railways with normal traffic conditions with the possibility of providing high-speed rail traffic. This technical method for rapid assessment of the reliability of span structures of beam railroad bridges be used as a basis for harmonizing National Standard and for the further evolution of the codes for HSR. Bridge authorities are therefore interested in agreed methods to assess the safety, reliability, durability of existing bridges.

Аннотация. Разработка методов экспресс оценки надежности пролетных строений балочных железнодорожных мостов актуально в связи с тенденцией к возрастанию нагрузок от обращающего грузового подвижного состава и скоростей движения на магистральном транспорте со смешанным грузопассажирским оборотом. Эта проблема особо актуальна при создании и внедрении специальных технических условий (СТУ) проектирования мостов на высокоскоростных магистралях (ВСМ), как и в Европе, так и в Америке идет активно процесс совершенствования нормативной базы и являются инновационными разработками в данной области. Нормативные документы СТУ учитывают только две противоположные тенденции. Первая – снижение эквивалентных нагрузок от специализированного высокоскоростного подвижного состава, вторая – увеличение динамических коэффициентов при увеличении скоростей движения до 350…400 км/ч. Одновременно разрабатываемые документы требуют обеспечения пропуска относительно тяжелой нагрузки от специального технологического подвижного состава при плановых работах по содержанию железнодорожного пути, а также при ликвидации последствий аварий и иных чрезвычайных ситуациях. Класс этой нагрузки соответствует С11, что составляет 78,5 % от нагрузки класса С14, являющегося расчетным для мостов на железных дорогах общего пользования. Авторы предлагают методику оценки надежности ограниченного пропуска по балочным пролетным строениям железнодорожного транспорта, нагрузка от которого на 10–20% превышает проектную расчетную нагрузку. Описано решение позволяющее оценить вероятность безотказной работы при отсутствии внезапного отказа на уровне 0,97–0,98. Такое решение актуально для железных дорог с обычным режимом движения с возможностью обеспечения проезда высокоскоростного состава. Представленный технический метод экспресс оценки надежности пролетных строений балочных железнодорожных мостов может использоваться в качестве основного инструмента для разработки национального стандарта и для дальнейшего развития нормативной базы для ВСМ. Управляющие компании заинтересованы в утверждении специализированных методов по оценке безопасности, надежности, прочности существующих мостов.

Introduction

A large number of eminent scientists, mechanics and engineers were involved in the study of reliability and the development of methods for its evaluation of various building systems. Considering the fact that this article deals with a certain element of the bridge structure – the beam span of the railway bridge, the following scientists and engineers deserve special attention: A.R. Rzhanicyn [1], K. Kapur and L. Lamberson [2], V.N. Smirnov [3, 5–8], V.V. Kondratov [4], V.V. Bolotin [9–11], J.G. Panovko [12] and many others.

Performance of the railway transportation network depends on the reliability of railway bridges. Developments in this field in the US sponsored by the U.S. Department of Transportation Research and Innovative Technology Administration [13].

Current high-speed railway (HSR) bridge design adopts the design concept which increases the stiffness of existing bridge introducing impact factor at the static load condition. However, given the extended total length and high speed of HSR system which has significant effect on resonance phenomenon, the in-depth evaluation of its dynamic performance shall be implemented. The optimal design of HSR bridges based on expected life-cycle cost (LCC) was very critical in securing the economic efficiency and the research has been underway in various ways [14].

The optimal policy has to be chosen based on minimum expected total LCC criterion including its effect on structural reliability and the expected costs associated with failure [15–18].

The results from the reliability analysis for the fatigue limit state are presented for various time periods from 10 to 100Â years and three cases of operating conditions [19–21].

As reported in Wisniewski et al. 2012, several years of research at National, European and International levels, including several European Projects, as well as practical implementations of these concepts on specific projects have demonstrated the benefits of incorporating advanced assessment and load rating in bridge assessment codes. However, the proposed advanced assessment methods for bridges as presented in the previous chapters are not yet included in most of the codes and recommendations or national or international regulations, where a standard basic assessment is normally applied. However, several countries have already included in their codes the possibility of using to some extent the proposed methods [22–27].

At the present moment, none is fully implementing all possible choices. It also becomes evident that USA and Canada are the countries where more of the proposed advanced methods are considered.

The European Convention for Constructional Steelwork (ECCS) has in its Technical Committee 6 – Fatigue (that also laid the basis for EN 1993 – Eurocode 3 – Part 1-9 – Fatigue) agreed to support the preparation of such European technical “Recommendations for the estimation of remaining Assessment of Existing Steel Structures; Remaining Fatigue Life First edition 2008 iv fatigue life”, that could be used as a basis for harmonising National procedures and for the further evolution of the Eurocodes [28].

This article is devoted to solving the problem related to the assessment of the reliability of beam span structures of railway bridges. The urgency of this problem stems from the need to improve the regulatory framework for the design of railway bridges, designed for high-speed traffic and mixed cargo and passenger traffic, and the development of special technical conditions (STC).

As the analysis of the existing regulatory framework shows, it is necessary to ensure that a relatively heavy load passes from the special technological rolling stock when planning work on the maintenance of the railway track, as well as during the liquidation of the consequences of accidents and other emergencies. The class of this load corresponds to C11, which is 78.5 % of the load of class C14, which is calculated for bridges on public railways.

In practical terms, the author proposes a technique for express estimation of the reliability of span structures, taking into account the skipping load exceeding the estimated design.

Allowable rail car loads are also expected to be increased by 10–20 % over the next few years. Knowledge of the current loadings to which railway bridges are subjected is imperative for accurate bridge evaluation.

Task description

Represented in foreign norms and rules (Eurocode, AAHSTO) methods for assessing the reliability of beam span structures of railway bridges include absolutely different algorithms for estimating and deducing the final result, which makes this express method developed and presented by the author in this article as original and separate as possible.

The live loads and dynamic amplification factors in the design codes are given for the design of new structures and can therefore be very conservative in some circumstances leading to structures failing their assessments. Consequently, it is often beneficial to use site-specific live loads and dynamic amplification factors when assessing existing railway bridges. In fact, this has been recognized worldwide.

The basis of the supposed approximate method for determining the reliability parameter and the probability of failure-free operation of the span structure according to the first limiting state (providing the carrying capacity) is the determination of the value of the mobile load intensities q (kN/m), corresponding to the limits of the normative and design fail-safe regions for given real geometric characteristics of the principal beams of span structure.

With this rapid assessment, it is considered that the refusal is of a sudden nature.

The failure group and the failure tree are not analyzed.

The intensity values indicated above are determined from the equation of the first limiting state:

$$2mkR^{\text{H}}A = n_1 p\Omega_p + n_2 q_{*}(1+\mu)\Omega_q, \tag{1}$$

where *m* – operating ratio;

k – material resistance factor;

n_1 and n_2 – respectively, the reliability coefficients for the constant and temporary loads;

R^H – the standard resistance of the material, the values of these quantities are regulated by the relevant documents (SNiP);

p and *q* – intensity of constant and temporary loads;

Ω_p and Ω_q – the area of the lines of influence of the bending moment loaded respectively by the constant and temporary loads.

From the equation of the limiting state (1), the values of the intensity of the movable load q_* corresponding to the boundary of the normative region of fail-safe operation:

$$q_* = \frac{2mkR^{\text{H}}A - n_1 p^{\text{H}} \Omega_p}{n_2(1+\mu)\Omega_q}. \quad (2)$$

The boundary of the calculated region of fail-safe operation corresponds to the value of the intensity of the movable load q_{**} obtained from equation (2) with $n_1 = n_2 = 1$, $m = 1$ и $k = 1$.

$$q_{**} = \frac{2R^{\text{H}}A - p^{\text{H}} \Omega_p}{(1+\mu)\Omega_q}. \quad (3)$$

Safety factor at pass of normative loading $q_* = q^{\text{H}}$ [1]:

$$\gamma = \frac{q_{**} - q_*}{\sqrt{\hat{q}_{**} + \hat{q}_*}} = \frac{\beta - 1}{\frac{1}{q_*}\sqrt{\hat{q}_{**} + \hat{q}_*}} = \frac{\beta - 1}{\sqrt{W_R^2 \beta^2 + W_q^2}}, \quad (4)$$

where $\beta = \frac{q_{**}}{q_*}$, $\hat{q}_{**}$ and $\hat{q}_*$ – variance of random variables,

W_R^2 and W_q^2 – coefficient of variation of the standard resistance and the normative load.

The probability of failure-free operation of the span structure when passing the normative load q is given by:

$$P = \frac{1}{2} + \Phi\left(\frac{\beta - 1}{\sqrt{W_R^2 \beta^2 + W_q^2}}\right), \quad (5)$$

where $\Phi\left(\frac{\beta - 1}{\sqrt{W_R^2 \beta^2 + W_q^2}}\right)$ – the value of the Laplace function.

If the load exceeds the normative one, according to SNiP, equation (5) takes the form:

$$P = \frac{1}{2} + \Phi\left(\frac{\beta' - 1}{\sqrt{W_R^2 \beta^2 + W_q^2}}\right), \quad (6)$$

where $\beta' = \dfrac{q_{**}}{q}$.

From the point of view of mathematical statistics, the mathematical expectation is shifted to the right and together with it the whole curve of the density of the load distribution without changing the shape of the curve.

We will estimate the value of the reliability index when passing over the span structure of the load, which is 15% higher than the standard load, with the values of the parameters $\beta = 1.1 \div 1.5$, $W_R = 0.05$ and $W_q = 0.0833$.

The results of calculating the reliability index as a function of the change in the calculated parameter β are shown in Figures 1 and 2, respectively.

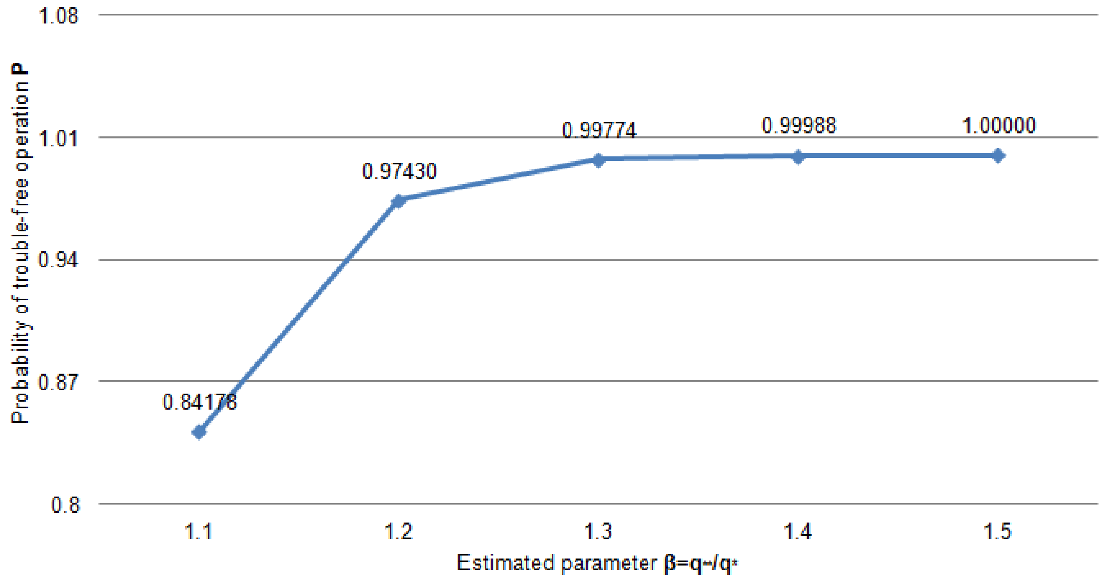

Figure 1. The values of the parameter P for the movement of the normative load

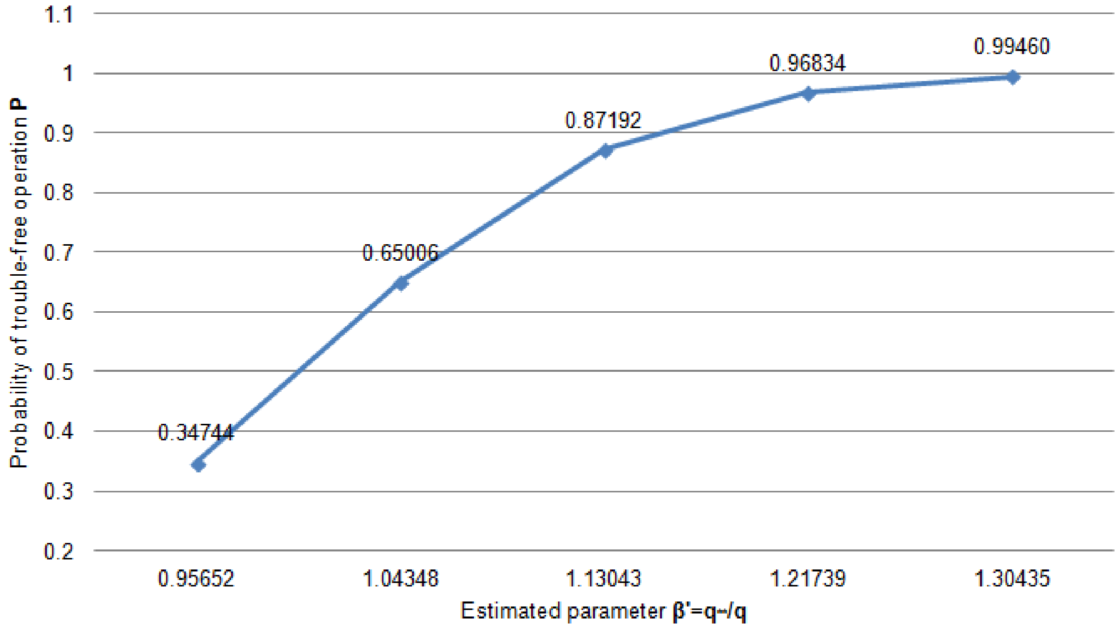

Figure 2. The values of the parameter P when moving the normative load, increased by 15%

Analyzing the graphs presented in Figures 1 and 2, it can be concluded that with an increase in the design load, there is a clear decrease in the reliability index, which is approximately 0.2 %.

Influence of the laws of distribution of extreme values of maxima for load and minima for strength

Equations 5 and 6 can be used when making the distribution laws of generalized loads and strengths different from the normal distribution laws.

For example, when accepting as distribution laws the Gumbel law (the law of distribution of extreme values) - the maximums for the load:

$$F(Q) = \exp\left[-\exp\left(-\frac{x-a_Q}{b_Q}\right)\right], \qquad (7)$$

and minima for strength:

$$F(R) = 1-\exp\left[-\exp\left(\frac{x-a_Q}{b_Q}\right)\right], \qquad (8)$$

using the first members of the Edgeworth series [2].

We obtain an analog of equation (1) for the probability of failure-free operation:

$$P = \frac{1}{2} + q\left(-\frac{a_R - a_Q + \Gamma'(1)(b_R + b_Q)}{\frac{\pi}{\sqrt{6}}\sqrt{b_R{}^2 + b_Q{}^2}}\right), \qquad (9)$$

where, $\Gamma'(1) = -0.57721$ – first derivative of the gamma function $\Gamma'(x)$ with respect to x at the point $x = 1$.

The analogues of equations (5) and (6) are:

$$P^{\text{H}} = \frac{1}{2} + \Phi\left(\frac{\beta - 1 + \Gamma'(1)\left(\frac{b_R + b_Q}{q_*}\right)}{\frac{\pi}{q_*}\sqrt{\frac{b_R{}^2 + b_Q{}^2}{6}}}\right), \qquad (10)$$

$$P = \frac{1}{2} + \Phi\left(\frac{\beta' - 1 + \Gamma'(1)\left(\frac{b_R + b_Q}{q}\right)}{\frac{\pi}{q}\sqrt{\frac{b_R{}^2 + b_Q{}^2}{6}}}\right). \qquad (11)$$

Application of the method for estimating the reliability of span structures intended for the movement of high-speed trains

When assessing the reliability of the span of bridges on highways designed exclusively for high-speed traffic, one should take into account the difference in the loading scheme of the influence lines by the time load in comparison with the loading scheme for Russian Construction Norms and Regulations SNiP 2.05.03-84 *.

In accordance with the "Instructions for the design of bridges for the main section of the Leningrad-Moscow high-speed passenger highway Center-South" (1990), a trainload was introduced from a specialized passenger electric vehicle with a design speed of up to 350 km/h in the form of a concentrated cargo Pi 180 kN and 170 kN.

Equivalent load is calculated by the formula:

$$q_{equal} = \frac{\sum P_i y_i}{\Omega}, \quad (12)$$

where, y_i – ordinate of the influence line under the load P_i;

Ω – the area of the influence line (for the length of the influence line λ = 50…100 м it was 33.89 kN/m and 29.36 kN / m, respectively, instead of 138.3 kN / m and 137 kN / m according to Russian Construction Norms and Regulations SNiP 2.05.03-84*).

The value of the dynamic coefficient $1+\mu$ increased and became equal to $1+\mu = 1+\frac{24}{30+\lambda}$ instead of $1+\mu = 1+\frac{18}{30+\lambda}$ in Russian Construction Norms and Regulations SNiP.

he load reliability factor is n_2 = 1.15 regardless of the length of the load.

The value of the intensity of the mobile load corresponding to the boundary of the normative fail-safe area can be determined from expression (2), taking into account the changed parameters.

Similarly, the expression (3) is used to determine the value of q **.

The value of the coefficient β determined by formula (4) differs little from that obtained for passenger-and-freight railways, since it does not depend on the dynamic coefficient very much on the value of the numerators of expressions (2) and (3).

The coefficient of load reliability for a span structure at λ = 50 m, calculated according to the "Instructions" and Russian Construction Norms and Regulations SNiP 2.05.03-84 * practically coincide.

In accordance with the STC for the design, construction and operation of the high-speed Moscow-Kazan-Yekaterinburg railroad developed at the MRIT in 2013, equivalent loads from high-speed rolling stock have increased for span structures of *l* = 50 m and 100 m, respectively 3 % and 1.7 %.

V.V. Kondratov on the basis of theoretical and experimental studies, a new approach to the designation of a dynamic coefficient for high-speed motion was proposed [3]:

$$1+\mu = 1+\alpha K + \frac{3}{20+\ell}, \quad (13)$$

where, $\alpha = \frac{v}{2 f \ell}$, *K*=0.8

f – basic frequency of free oscillations of the span structure, Hz;

ℓ – calculated span, m;

v – travel speed, m/sec.

For span structures ℓ = 50…100 m, the values of the dynamic coefficient are 1.3 ... 1.2 instead of the minimum value adopted for Russian Construction Norms and Regulations SNiP 2.05.03-84 * when calculating for strength 1.15..

According to the requirements of the normative documents for the construction of bridges at the bridge, these bridges must provide access to technological structures and transport units, with loading characteristics not exceeding the normative load of C11 (for the span structures $\ell = 50...100$ m is 108.66 kN/m and 107.64 kN/m, respectively 3.2 times the value of the standard load for high-speed rolling stock) at speeds of up to 120 km/h [4].

Consequently, in most cases it is the admission of a special load that is calculated to ensure the guaranteed load-bearing capacity of span structures.

Results and Discussion

Taking into account the structural reserves of strength, reflected in the values of the geometric characteristics of section A, and taking into account the reliability coefficients adopted in Russian Construction Norms and Regulations SNiP for materials and loads under extreme conditions, in a limited number of implementations, the load on beam girder bridges is allowed to exceed the design load by 20 ... 25% if the probability of failure-free operation of span structures (no sudden failures) is not lower than 0.95.

The AASHTO LRFR code (AASHTO LRFR, 2003) for Load and Resistance Factor Rating (LRFR) uses similar reliability based assessment principles and the load rating process to those of CAN/CSA-S6-06 [29, 30].

If, as a limiting state, the plastic hinge is formed in the main beam and the moment of resistance W is replaced by the plastic moment of resistance W_{pl}, then $A=\frac{W_{pl}h}{2}$, where, *h* – height of the main beam, the probability of failure-free operation when the above load is skipped increases to a value of 0.97 ... 0.98.

Due to the greater static stability of the load from the high-speed rolling stock, the probability of failure-free operation for the span structures of bridges on the HSR at a 10% excess of the standard load from the high-speed rolling stock is 0.99.

If the load from the special rolling stock is missed in case the load of the normative value for the C11 class is exceeded by 27 %, which corresponds to the skipping of the load of the C14 class, the reliability index decreases by 5.8 %.

Conclusions

1. The technique of express evaluation of beam span structures of railway bridges located on the railway network is developed, both with the usual driving mode and with high-speed.
2. The developed methodology allows to justify the possibility of skipping the load exceeding the design estimate for planned maintenance of the railway track, as well as for the elimination of the consequences of accidents and other emergencies with an acceptable degree of reliability.
3. This technique is based on special technical conditions (STU) and complements and is consistent with the foreign technical documentation related to the design of railway bridges on high-speed highways.

This technical method for rapid assessment of the reliability of span structures of beam railroad bridges be used as a basis for harmonizing National Standard and for the further evolution of the codes. Bridge authorities are therefore interested in agreed methods to assess the safety, reliability, durability of existing bridges.

The need to increase the lifetime of beam girder bridges, which have the highest percentage of distribution worldwide, and require a continuous assessment of operational reliability, determines the relevance of the calculations.

The application of the theoretical provisions outlined in the work makes it possible to provide the methodological support for the integrated system for assessing the suitability for the operation of beam girder bridge bridges with significant operating times and with increased operational loads, both in load and speed, which corresponds to the recent trend in the operation of the railway transport.

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