Experience non-destructive testing of the metal of bridge structures

A N Beskopylny*, N L Vernezi†, A A Veremeenko‡, R M Arakelyan§

Don State Technical University, 1, Gagarina sq, Rostov-on-Don, 344010, Russia

E-mail: besk-an@yandex.ru

Abstract. The paper described the history of the use of materials in the construction of bridges, the examples of the significant disasters associated with the destruction of bridges in various countries. The problems that inevitably arise during the inspection of bridges and assessment of their bearing capacity are considered. The requirements for monitoring of the strength characteristics are given. The list of controlled characteristics is presented. A non-destructive method for determining these mechanical characteristics by impact pressing the conical indenter is considered. The analysis of the characteristics of the railway bridges in the city of Belaya Kalitva and Novocherkassk was made. These characteristics were compared with the properties of the metals used in construction in different years. The statistical analysis of the obtained data was made.

Introduction

In the past, the materials for the construction of bridges were wood and stone. By the end of the XIX century cast iron, iron, and then steel began to be used in the construction of bridges. Unfortunately, there have been dozens of disasters due to their destruction. The main reason was the failure of the strength of the structural elements under the dynamic loads. So, the cast iron bridge in Derbyshire (England) was destroyed in 1860. Several bridges in 1861 (the Platt bridge, USA), in 1879 (Tei bridge in Dundee, England), in 1905 (the Egyptian bridge In St. Petersburg) were broken because of the strength failure. Recently, the major disaster occurred in 2003 with the destruction of the railway bridge in Pennsylvania (USA). Thus, there is an actual problem of estimating and predicting the durability of bridge structures [1-4].

Evaluation of the bearing capacity of any existing metal bridge is to identify the predominance of its strength capabilities over the disturbing effects. Perfect software systems created nowadays for the assessment of the stress-strain state of structural elements in combination with modern computer technology allow to quickly and accurately assess the disturbing effects. To determine the strength capabilities of the material of structural elements at different points is a complex and time-consuming task, while the characteristics of the source material, as practice shows, do not always meet the requirements in the documentation.

Over time, due to loads, temperatures, corrosion, and others they can undergo significant changes, and periodic destructive control of mechanical characteristics with cutting and testing of samples is practically impossible. The use of non-destructive testing devices can solve these difficulties.
Thus, in [5] the question of estimating the yield strength from the "stress-strain" dependence obtained by pressing the spherical tip is considered. In [6-8] indentation method was successfully used to determine the strength characteristics of welded joints of structural steels.

However, the resistance of materials to external factors is characterized not by anyone, but by a set of mechanical properties that must be known and measured directly on the bridge. The most important mechanical characteristics are hardness HB, yield strength $\sigma_y$ and strength $\sigma_u$, elongation $\delta_5$ and toughness KCU. It should be noted the features of mechanical characteristics, namely: their random nature; their relationship so that each study area of the design is necessary to assess the complex characteristics; their dependence on the duration and nature of previous loads. Evaluation of strength capabilities in the survey work of metal structures involves obtaining values of yield strength, tensile strength, and elongation.

Thus, the primary purpose of the paper is to introduce the features and experience of the use of a new method that was developed for express estimation of the steel structure mechanical state at any point [9,10].

Materials and methods

For the assessment of the mechanical characteristics of the surveyed railway bridges in Belaya Kalitva and G. Novocherkassk, the device for non-destructive measurement of the strength of metal was used for various tasks [11,12]. The device is based on the analysis of the shock characteristics study (extreme values of the velocity and acceleration, and depth) during the indentation of the 90 degrees cone with impact energies of 0.16 J. These characteristics are related to the standard parameters: HB, $\sigma_y$, $\sigma_u$, and $\delta_5$ (in the development of the instrument). The device almost instantly allows getting the values of these characteristics at any point of the structure.

Before the inspection of bridges, the standard tensile tests and proving of the device for non-destructive measurement the mechanical characteristics were previously subjected. The results of these tests are shown in table 1.

Table 1. Ultimate strength and yield strength according to the results of standardized tensile tests (1) and impact indentation (2)

| Steel | Ultimate strength $\sigma_{u1}$, [MPa] | Ultimate strength $\sigma_{u2}$, [MPa] | Error, [%] |
|-------|----------------------------------------|----------------------------------------|------------|
| 08    | 2                                      | 3                                      | 4          |
| 1     | 314                                    | 313                                    | 0.2        |
|       | 296                                    | 313                                    | -5.9       |
|       | 306                                    | 306                                    | 0          |
| 15    | 476                                    | 471                                    | -0.7       |

| Steel | Yield strength $\sigma_{y1}$, [MPa] | Yield strength $\sigma_{y2}$, [MPa] | Error, [%] |
|-------|------------------------------------|------------------------------------|------------|
| 08    | 204                                | 191                                | 6.2        |
|       | 192                                | 194                                | -0.7       |
|       | 201                                | 186                                | 7.6        |
| 15    | 281                                | 278                                | 0.9        |
|       | 252                                | 246                                | 2.2        |

The materials are listed in table 1 - 08 Steel (C 0.07%, Si 0.01%, Mn 0.03%, Ni 0.06%, Cr 0.03%, Al 0.07 %, Cu 0.06%) and 15 Steel (C 0.15%, Si 0.07%, Mn 0.05%, Ni 0.25%, Cr 0.25%, Cu 0.25%).

The error of estimation of characteristics did not exceed 8 %. Earlier studies have shown that there is no significant effect on the device obtained by assessing the mechanical characteristics of the possible stress state of the surveyed metal.
During the examination of the bridges in the city of Belaya Kalitva (BK) and Novocherkassk (N), the following methodology was applied. On two farms of two of four bridge spans (BK) 143 places were surveyed, on each of which the sander removed a layer of paint to pure metal and made 7-10 measurements; on two farms of the bridge (N) 87 places were surveyed in the same way. Thus, statistical data on measurements of mechanical characteristics were obtained.

Results and discussion

Long-term operation of steel constructions of the bridges requires regular monitoring and periodic diagnosis of their technical statement. In most cases, we can not manufacture the specimens from existing steel structure and test them by tensile equipment. Under the influence of external loads, temperatures, corrosion, and others, the properties of bridge steel are changed that have to be determined at any point of the structure.

Figure 1 presents the results of the approximation of empirical values of hardness for compliance with the normal and Weibull distribution law (selected curves) with three parameters, the probability density of which have the general form

\[
f(x) = \frac{k}{b} \left( \frac{x - \mu}{b} \right)^{k-1} \exp \left( \frac{x - \mu}{b} \right)
\]

(1)

where \( \mu \) – shift parameter, \( b \) – scale parameter, \( k \) – form parameter.

Figure 1. Histograms and probability distribution density of hardness HB in the metal of the first span (1 PR) of the bridge in Belaya Kalitva:

- Normal,
- 3-parameters Weibull

These bridges were built in 1947 – 1948, and during the period of operation to the present days, they run under cyclic loading from the passing railway trains. The bridge steel for 70 years of operation was corroded and could change its properties due to fatigue damage.

Figure 2 shows the results of the approximation of empirical values of ultimate strength for compliance with the normal and 3 parameters Weibull distribution law.
Figure 2. Histograms and probability distribution density of ultimate strength $\sigma_u$ in the metal of the first span (1 PR) of the bridge in Belaya.

Kalitva: — Normal, — 3-parameters Weibull

From a practical point of view, the minimum value in the general population is of interest. For each place, the minimum values were selected and already processed for compliance with the three-parameter Weibull law. The results are shown in table 2.

Table 2. Estimation of the mechanical characteristics with the three-parameter Weibull distribution 1 (1PR) and 2 (1PR) spans in Belaya Kalitva and left (LF), and right (PF) trusses Novocherkassk.

| Mechanical characteristics | Belaya Kalitva | | Novocherkassk | |
|---------------------------|---------------|---|---------------|---|
|                           | Shift parameter, $\mu$ | Form parameter, $\beta$ | The range of minimum value, [%] | Shift parameter, $\mu$ | Form parameter, $\beta$ | The range of minimum value, [%] |
| 1PR 2PR 1PR 2PR 1PR 2PR 1PR 2PR | LF PF LF PF LF PF | | | | | |
| HB 78 72 1.64 2.4 117-150 66-92 | 92 89 2.69 3.33 | 15 -16 29-33 | | | | |
| $\delta$, [%] 16 14 4.2 3.33 33-206 27-193 | 25 22 2.51 2.77 | 19-76 19-86 | | | | |
| $\sigma_y$, [MPa] 172 158 0.9 1.77 162-94 119-75 | 173 171 2.84 2.49 | 20-12 24-33 | | | | |
| $\sigma_u$, [MPa] 252 259 1.98 1.35 169-67 127-49 | 288 267 3.15 2.81 | 35-12 72-27 | | | | |

Table 3 shows the statistical characteristics, parameters of distribution laws and criterion of agreement Von Mises $\omega^2$. It is seen that 3-parameter Weibull law describes the sample data better than Normal law.

Table 3. Statistical characteristics of mechanical properties (MP), parameters of distribution laws and criterion of agreement $\omega^2$.

| MP | | Normal law | Weibull law | |
|----|----------------|-------------|-------------|---|
| | Sample mean, $\bar{X}$ | Standard deviation, $s$ | Von Mises criterion, $\omega^2$ | Scale, b | Form, $k$ | Shift, $\mu$ | Von Mises criterion, $\omega^2$ |
| HB | 128 | 5.06 | 1.206 | 14.66 | 2.8 | 115.24 | 1.13 |
| $\sigma_y$, [MPa] | 288 | 26.29 | 7.042 | 59.47 | 2.11 | 235.82 | 2.47 |
The conducted studies allow us to substantiate the stochastic model of steel strength, as a vector of minimal and consistent with each other (from the condition of viscous fracture) values of the mechanical characteristics of the metal, which can be applied to machine parts [13].

Summary

An important conclusion that can be made after analyzing the table is a significant difference in the dispersion of characteristics by the volume of the metal of bridges in Belaya Kalitva and Novocherkassk. So, for the Belaya Kalitva bridge (BK), the deviation from the parameter \( \mu \) fluctuates within 49% - 206%. The same for the Novocherkassk bridge (N) - from 12% to 86%. The fact corresponds well with the shape parameters of the theoretical distribution functions approximating the experimental data. Such dispersion of values is due to the time of the construction of bridges — 1947, when all possible scrap, including the metal of broken military equipment, was used for the steel production.

The evaluation of the absolute values of the parameter \( \mu \) of the distribution of the minimum values of mechanical characteristics contains the following. The average \( \mu \) value of the bridge metal for hardening is 75 HB, for relative elongation ~-15%, for yield strength — 165 MPa, for strength — 255.5 MPa. Such values of mechanical characteristics have no analogs in the steels produced today in the Russian Federation. Almost all of them are close to the characteristics of pure iron, except for \( \mu \) for relative elongation, which, with a huge range of sample values, is lower than that of iron.

The same for the metal of the bridge H: the average value of \( \mu \) for hardness is 90.5 HB, for \( \delta \) - 23.5%, for \( \sigma_y \) - 172 MPa, for \( \sigma_u \) - 277.5 MPa. According to these values, the metal can correspond to steel of ordinary quality St0 or quality steel 08.

The proposed algorithm of non-destructive evaluation of the minimum values of the mechanical characteristics of the metal is possible for use in the design and reconstruction of bridges and other steel structures.

References

[1] Moussa C, Hernot X, Bartier O, Delattre G, Mauvoisin G 2014 Identification of the hardening law of materials with spherical indentation using the average representative strain for several penetration depths (Materials Science and Engineering) A. 606 (2014) 409–416.
[2] A Beskopylny, Lyapin A, Kadomtsev M and Veremeenko A 2018 Complex method of defects diagnostics in underground structures (MATEC Web of Conferences) 146 02013.
[3] Beskopylny A N, Lyapin A A, Andreev V I 2017 Layered structures mechanical properties assessment by dynamic tests (MATEC Web of Conferences) 117 00018
[4] Beskopylny A, Veremeenko A, Kadomtseva E, Beskopynia N 2017 Non-destructive test of steel structures by conical indentation (MATEC Web of Conferences) 129 02046.
[5] Dipen K P, Surya R K 2016 Correlation of spherical nanoindentation stress-strain curves to simple compression stress-strain curves for elastic-plastic isotropic materials using finite element models (Acta Materialia) 112 295-302.
[6] Belen'kii D M, Beskopyl'nyi A N, Vernezi N L, Shamraev L G 1997 Determination of the strength of butt welded joints (Welding International) 11 642-645.
[7] Arzola N, Hernández E Experimental characterization of fatigue strength in butt welded joint considering the geometry and the effect of cooling rate of the weld (Journal of Physics, Conference Series) 843 (1) 012047.
[8] Jung J Kim, Thai-Hoan Pham and Seung-Eock Kim 2015 *Instrumented indentation testing and FE analysis for investigation of mechanical properties in structural steel weld zone* (International Journal of Mechanical Sciences) **103** 265-274.

[9] Belen’kii D M, Beskopylny A N, Shamraev L G 1998 *Determination of technological and service characteristics of steels* (Industrial laboratory) **64 (5)** 340-343.

[10] Beskopylny A N, Veremeenko A A, Yazyev B M 2017 *Metal structures diagnosis by truncated cone indentation* (MATEC Web of Conferences) **106** 04004.

[11] Beskopylny A N, Kadomtseva E E, Strelnikov G P, Berdnik Y A 2017 *Stress-strain state of reinforced bimodulus beam on an elastic foundation* (IOP Conf. Ser.: Earth Environ. Sci.) **90** 012064.

[12] Beskopylny A N, Kadomtseva E E, Strelnikov G P 2017 *Numerical study of the stress-strain state of reinforced plate on an elastic foundation by the bubnov-galerkin method* (IOP Conf. Ser.: Earth Environ. Sci.) **90** 012017.

[13] Beskopylny A N, Rykov V B, Zubrilina E M, Chistyakov A D 2018 *Agricultural machine parts quality control by dynamic non-destructive methods* (MATEC Web of Conferences) **226** 04034.

[14] Rogovenko T N, Zaitseva M M 2017 *Use of statistical simulation in construction planning* (MATEC Web of Conferences) **106** 08011.