The Methodology of Experimental Bending Moments Determination in Bridge Span Structures

Yuriy Sobko(✉)

Lviv Polytechnic National University, Lviv 79013, Ukraine
sobko.yuriy@ua.sika.com

Abstract. The article presents results of the study of the experimental bending moments in the nonlinear area of section deformation determined by the proposed algorithm and showed practically accurate using for close to the real size constructions of the full scale T-beam length 13,5 m with rigid/frame reinforcement. This beam was separated from adjacent beams of the bridge deck superstructure by cutting of welded metal plates of T-beam shelves and diaphragms. Then a testing metal structure system of individual design and execution, which consisted of a truss length of 15,0 m and a height of 2,5 m was installed. By means of ties and traverses system the external testing load was transferred to the existing bridge supports. The technique and algorithm of experimental bending moments determining by the values of beams cross sections vertical displacements obtained in field tests of bridge deck structures, which allow to take into account the physical nonlinearity of RC elements deformation, as well as the presence of existing defects and initial deformed and strained state of spatial structure.

Keywords: Real size constructions · Rigid/Frame reinforcement · Bridge span structures · Reinforce concrete · T-girder bridge deck structures

1 Introduction

One of the most common types of bridges constructions are T-girder bridge deck structures with welded rigid so called "frame" reinforcement cages [1–5]. These are road bridges with and without of transverse beams and main beams, simply supported, regular structure, small and medium span, which were designed for loads of class H-18, NK-80. The specificity of such girder structures is that with a rather thin shell of T-beams geometry, i.e. with low own weight, the cross sections are supersaturated with reinforcement steel (percentage of reinforcement up to 5%), which is not a conventional feature of classical reinforced concrete elements. Along the girder welded reinforcement cages are made with breaks in the rods [6–10]. It means that the amount of reinforcement and, accordingly, the stiffness in the cross sections where the rods was broken is variable, i.e. the spatial system of the girder structure along the girder is irregular. These girder structures have been in operation for about 30–40 years. They were designed by the method of allowable stresses, which indicates the presence of

Z. Blikharskyy (Ed.): EcoComfort 2020, LNCE 100, pp. 443–450, 2021.
https://doi.org/10.1007/978-3-030-57340-9_54

certain strength reserves that need to be used rationally, for example in determining how to reconstruct, widening and increase of structure load bearing capacity. To do this, it is important to have a real values of the girder structures cross-sections stress-strained state of the elements.

This task has already been solved earlier in KADI, LPI, BildorNDI and in the other institutions [11–13]. There were studies the bridge girder structures on Plexiglas models and reinforced concrete as well. As a result of tests, experimental data of sections vertical displacements were obtained, which determined the experimental particles of external force/bending moments, while mistakenly believing that the stiffness of the sections remains constant and equal to the design value Ecired according to Eq. (1):

$$f_{ij} = \frac{Fw_{ij}}{\sum\limits_{i,j=1}^{n,m} w_{ij}}, \quad (1)$$

where F is the external test load; fij - the share of external test load on the i-th beam in the j-th section; wij- vertical component of displacement of the i-th beam in the j-th section; n is the number of beams in cross section; m is the number of calculated cross-sections along the span.

The proportion of external force (experimental bending moments) was also determined by another known method from the measured support reactions of beams with regular and irregular stiffness in the cross section of girder bridge deck structures, assuming that the share of external load transmitted to the i-th beam of the span system is equal to the sum of the support reactions of this beam according to Eq. (2):

$$f_i = R_{Ai} + R_{Bi};\ i = 1, 2, 3 \ldots n, \quad (2)$$

where R_{Ai} and R_{Bi} – support reactions of i-th beam.

It should be noted that the Eq. (1), (2) are valid for elastic spatial beam systems with regular in cross section stiffness, assuming that the fraction of force F_i acts only in the transverse cross section of bridge deck where external force F in the form of concentrated force is applied.

As can be seen, the previous investigations did not determine the experimental bending moments and stiffness, taking into account the nonlinear behavior of reinforced concrete sections deformation with cracks. This issue was first solved in the laboratory R&D-88 of National University "Lviv Polytechnic" [14, 15] by developing a new method for determining the experimental bending moments, taking into account cracking and nonlinearity of RC sections deformation [16–18]. The essence of the method was that the bending moments in the cross sections of the reinforced concrete beam under a certain scheme of application of external load and certain conditions of supporting are a function of the average relative deformations of concrete and reinforcement steel of these sections in Eqs. (3), (4):

$$M_i = F(\varepsilon_{cmi}), \tag{3}$$

$$M_i = F(\varepsilon_{smi}), \tag{4}$$

where ε_{cmi}, ε_{smi} experimental values of average relative deformations of concrete and steel; i = 1, 2, 3,…, n - the number of cross sections of the beam that was investigated; M – beam's bending moment in the i-th section.

Therefore, after experimental testing the bridge span structure according to a similar loading scheme and obtaining experimental values of average relative deformations of concrete and steel in beams cross sections in the girder structure found the appropriate experimental bending moments over the entire load range – in the elastic and elastic-plastic stages performance.

Further development the method of experimental moments determining in girder span structures sections taking into account the nonlinearity of RC elements based on deformation diagrams of bridge reference beams should be continued in the direction of using the differential equation of bent axis with curvature determining by measured vertical displacements of sections and experimental average strains of concrete and steel as well. These issues were addressed in this paper.

2 Experimental Research Methodology and Main Results

Tests of the full scale T-beam length 13,5 m with rigid/frame reinforcement were made (Fig. 1). This beam was separated from adjacent beams of the bridge deck superstructure by cutting of welded metal plates of T-beam shelves and diaphragms. Then a testing metal structure system of individual design and execution, which consisted of a truss length of 15,0 m and a height of 2,5 m was installed. By means of ties and traverses system the external testing load was transferred to the existing bridge supports (Fig. 1a, b). Measurements of deformations were performed with mechanical microindicators based on 250 mm distance, which allowed to obtain the values of the average relative deformations of the RC sections. To measure the deformations of the reinforcement steel, special holders were welded at the level of the lower reinforcing rod center of gravity (Fig. 1, c). Vertical displacements were measured by deflectors 6PAO in the same sections. Crack formation was observed to determine the width of crack opening with a microscope. If possible, all measuring instruments were duplicated. As a result, according to the experimental data in the investigated sections, reference diagrams of concrete and steel deformations were received, as well as graphical dependences the change in the initial stiffness of the cross sections of the beams. Figure 2 presents these diagrams for the most characteristic section 2-2 in the middle part of the beam.

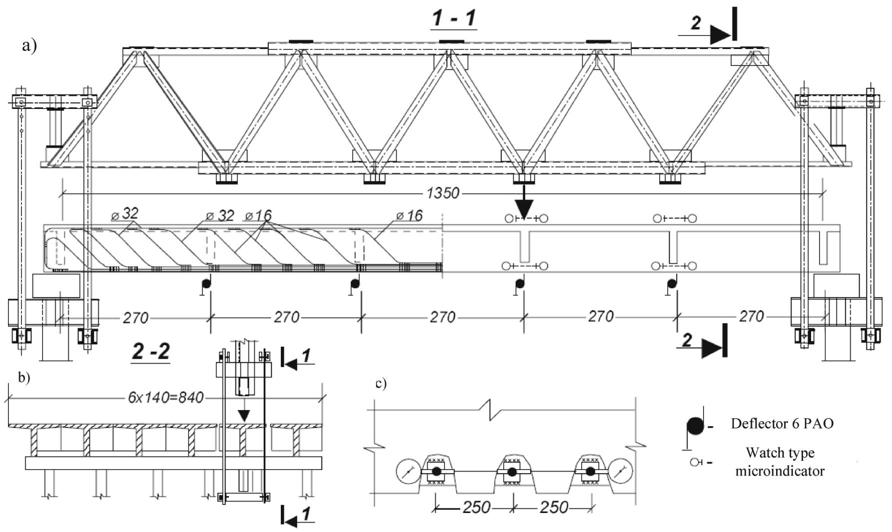

Fig. 1. The bridge beam with rigid/frame reinforcement and testing steel truss system general view: a - facade; b - cross section; c - a general view of mechanical watch type micro indicators installation.

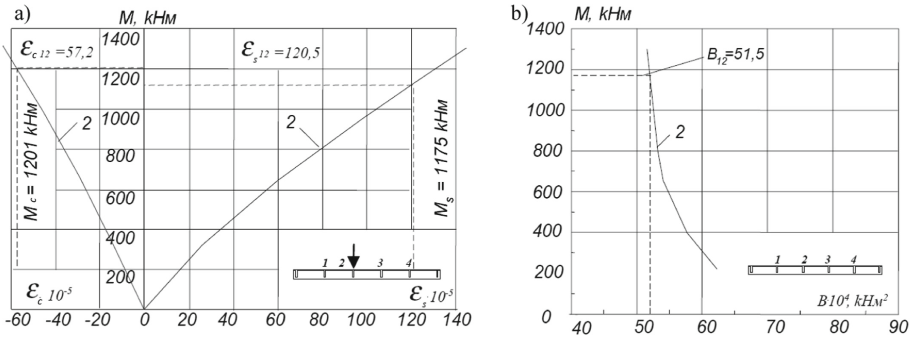

Fig. 2. The main experimental results of reference beam: a - reference graphs of concrete and steel relative deformations; b - reference beam stiffness diagram.

The bridge deck superstructure was tested using a similar method. The experimental data matrix of the relative deformations ε_c, ε_s and vertical displacements w_z in the cross sections of the beams was obtained. Consider as an example the most characteristic section 2–2 in the middle part of the span under loading with a concentration force F = 800 kN. In this section, the following values of relative deformations were obtained: ε_c = 0,0005721, ε_s = 0,001205. Next, according to the deformation diagrams of reference beam (Fig. 2,a) determine the experimental bending moments in the elastic-plastic stage of operation, acting in the first beam from the force F = 800 kN: $M_{s2\text{-}2}$ = 1175 kNm (for ε_s), $M_{c2\text{-}2}$ = 1201 kNm (for ε_c,). The average experimental bending moment was $M_{exp2\text{-}2}$ = 1186 kNm. Similarly it was determined for all sections thought the deck superstructure [1].

Consider the differential Eq. (5) of the beam bended axis:

$$y'' = \frac{M}{B}, \tag{5}$$

where y'' - cross section curvature under bending; B - stiffness of the section in the area with cracks.

The real experimental cross sections curvature can be determined from experimental data of average relative deformations Eq. (6):

$$y'' = \frac{1}{r} = \frac{\varepsilon_{cm} + \varepsilon_{sm}}{h}, \tag{6}$$

where ε_{cm} and ε_{sm} - experimental values of average relative deformations of concrete and steel; h - the distance from the concrete upper fiber to the center of gravity of the reinforcing welded cage lower rod.

Having found the value of the experimental curvature and the corresponding stiffness of the section in the area with cracks, from Eq. (5) it is easy to determine the value of M_{exp} in this section.

The experimental curvature can also be determined by the measured vertical displacements by drawing their longitudinal graphs in the beams of the deck girder structure [2]. According to the experimental graph of vertical displacements (Fig. 3,a), it is possible to write the equation of curvature, which is based on regression analysis (Fig. 3,b). For the first beam of the deck girder superstructure when loaded with a force F = 800 kN in section 2–2, the Eq. (7) will have the form:

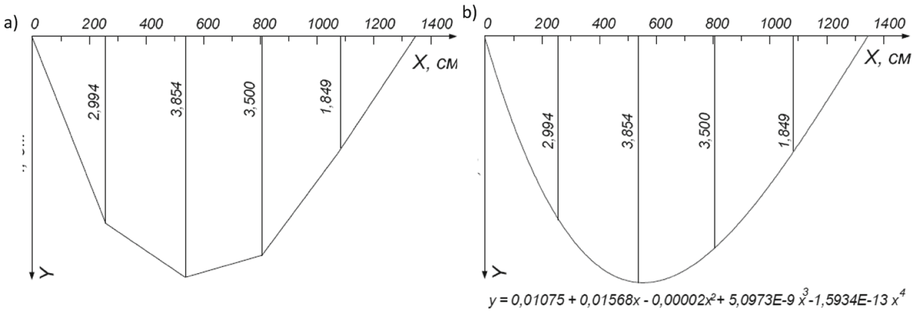

Fig. 3. Vertical displacement of first beam of deck superstructure: a – experimental; b – by regression analysis.

$$y = 0.010750 + 0.01568x - 0.00002x^2 + 5.0973e - 9x^3 - 1.5934e - 13x^4, \quad (7)$$

where y - vertical displacement, cm; x - cross-sectional distance, cm.

By differentiating the Eq. (7) twice by x, we obtain the following Eq. (8) of curvature:

$$\frac{d^2y}{dx^2} = y'' = -0.00004 + 30.582e - 9x - 19.121e - 13x^2. \quad (8)$$

Substituting the section coordinate x = 540 cm, we obtain y'' = 2,355·10^{-5} cm^{-1}.
The experimental curvature value Eq. (9) in the same cross section by the Eq. (6):

$$y'' = \frac{1}{r} = \frac{\varepsilon_{cm} + \varepsilon_{sm}}{h} = 2.235 \cdot 10^{-5} \mathrm{cm}^{-1}. \quad (9)$$

As could see, these values obtained by two independent methods are almost the same, which indicates the possibility of their use independently of each other.

3 Algorithm of Determining the Experimental Bending Moments by Experimental Curvature

From tests data of a reference bridge beam similar on a design, conditions of supporting and loading to beams of a girder deck superstructure, to draw the diagram (M–B_{exp}).

By the tests of the girder deck superstructure get experimental data of the average relative deformations and displacements; determine the experimental curvature of the bended axis of the sections by Eqs. (6), (7). By iterative method from the diagram (M–B_{exp}) determine the appropriate experimental cross-sectional stiffness in the area with cracks, while:

- in the first step to accept $B = E_c\ I_{red}$ and determine accordingly M_I;
- in the second step for M_I determine the stiffness B_{II} and calculate appropriate moment M_{II};
- in the third and subsequent steps, repeat the steps as in step II; calculation is ending if: $(M_i - M_{i-1})/M_i < 0{,}05$.

4 An Example the Experimental Bending Moments Determining

As an example, we define the experimental bending moments in section 2-2 according to the diagram (M-B_{exp}) (Fig. 2, b) and the above algorithm:

– when determined the y'' by the formula (6)
  - I-st step M_I = 2,235960 = 2145 kNm;
  - II-nd step M_{II} = 2,235505 = 1128,6 kNm;
  - III-rd step M_{III} = 2,235510 = 1139,8 kNm.

As can be seen, already in the third step of iterations the stiffness practically does not change (because the diagram has a gentle character, which is a characteristic feature of the reinforced beams with frame cage reinforcement) and the necessary convergence of results is reached.

– when determined the y″ by the Eq. (7)
  - I-st step M_I = 2,355960 = 2310 kNm;
  - II-nd step M_{II} = 2,355505 = 1215 kNm;
  - III-rd step M_{III} = 2,355510 = 1201 kNm

Comparing the obtained values of the experimental moments in the cross section 2–2 of the first beam of the bridge deck girder structure, determined by the methodology and the above mentioned method found that the discrepancy is: for Eq. (6) – 3,5%, for Eq. (7) - + 1,6%, which indicates a practical coincidence of results according to the proposed algorithm and method.

5 Conclusions

The experimental bending moments in the nonlinear area of section deformation determined by the proposed algorithm showed practically accurate and close to the real object results. In addition, this technique has its advantages: there is no need to determine the experimental average relative deformations ε_{cm}, ε_{cm} when testing girder deck structures and, as a consequence, reducing the complexity of work in preparation for testing, as well as reducing the time of testing and in-house work important in engineering practice.

References

1. Blikharskyy, Z., Brózda, K., Selejdak, J.: Effectivenes of strengthening loaded RC beams with FRCM system. Arch. Civ. Eng. **64**(3), 3–13 (2018)
2. Blikharskyy, Z., Vashkevych, R., Vegera, P., Blikharskyy, Y.: Crack resistance of RC beams on the shear. In: Lecture Notes in Civil Engineering, vol. 47, pp. 17–24 (2020). https://doi.org/10.1007/978-3-030-27011-7_3
3. Krainskyi, P., Blikharskyy, Y., Khmil, R., Vegera, P.: Crack resistance of RC columns strengthened by jacketing. In: Lecture Notes in Civil Engineering, vol. 47, pp. 195–201 (2020). https://doi.org/10.1007/978-3-030-27011-7_25
4. Selejdak, J., Blikharskyy Y., Khmil R., Blikharskyy Z.: Calculation of reinforced concrete columns strengthened by CFRP. In: Lecture Notes in Civil Engineering, vol. 47, pp. 400–410 (2020). https://doi.org/10.1007/978-3-030-27011-7_51
5. Vegera, P., Vashkevych, R., Blikharskyy, Z.: Fracture toughness of RC beams with different shear span. In: MATEC Web of Conferences, vol. 174, p. 02021 (2018). https://doi.org/10.1051/matecconf/201817402021
6. Blikhars'kyi, Y.Z.: Anisotropy of the mechanical properties of thermally hardened a500s reinforcement. Mater. Sci. **55**, 175–180 (2019). https://doi.org/10.1007/s11003-019-00285-0

7. Kharchenko, Y.V., Blikharskyy, Z.Y., Vira, V.V., Vasyliv, B.D.: Study of Structural changes in a nickel oxide containing anode material during reduction and oxidation at 600 °C. In: Fesenko, O., Yatsenko, L. (eds.) Nanocomposites, Nanostructures, and Their Applications. NANO 2018. Springer Proceedings in Physics, vol. 221. Springer, Cham (2019). https://doi.org/10.1007/978-3-030-17759-1_42
8. Kharchenko, Y., Blikharskyy, Z., Vira, V. Vasyliv, B., Vasyliv, B: Study of nanostructural changes in a Ni-containing cermet material during reduction and oxidation at 600 °C. Appl. Nanosci. (2020). https://doi.org/10.1007/s13204-020-01391-1
9. Lobodanov, M., Vegera, P., Blikharskyy, Z.: Planning Experiment for researching reinforced concrete beams with damages. In: Lecture Notes in Civil Engineering, vol. 47, pp. 243–250 (2020). https://doi.org/10.1007/978-3-030-27011-7_31
10. Zhang, Q., Mol'kov, Y.V., Sobko, Y.M., et al.: Determination of the mechanical characteristics and specific fracture energy of thermally hardened reinforcement. Mater. Sci. **50**, 824–829 (2015). https://doi.org/10.1007/s11003-015-9789-9
11. Blikharskyy Z., Khmil, R., Vegera, P.: Shear strength of reinforced concrete beams strengthened by PBO fiber mesh under loading. In: MATEC Web of Conferences, vol. 116, p. 02006 (2017). https://doi.org/10.1051/matecconf/201711602006
12. Bobalo, T., Blikharskyy, Y., Kopiika, N., Volynets, M.: Serviceability of RC beams reinforced with high strength rebar's and steel plate. In: Lecture Notes in Civil Engineering, vol. 47, pp. 25–33 (2020). https://doi.org/10.1007/978-3-030-27011-7_4
13. Khmil, R., Tytarenko, R., Blikharskyy, Y., Vashkevych, R.: Influence of load level during strengthening of reinforced concrete beams on their reliability. In: IOP Conference Series: Materials Science and Engineering, vol. 708, no. 1, p. 012054 (2019)
14. Bobalo, T., Blikharskyy, Y., Kopiika, N., Volynets, M.: Theoretical analysis of RC beams reinforced with high strength rebar's and steel plate. In: IOP Conference Series: Materials Science and Engineering, vol. 708, no. 1, p. 012045 (2019)
15. Krainskyi, P., Vegera, P., Khmil, R., Blikharskyy, Z.: Theoretical calculation method for crack resistance of jacketed RC columns. In: IOP Conference Series: Materials Science and Engineering, vol. 708, no. 1, p. 012059 (2019)
16. Blikharskyy, Y., Kopiika, N., Selejdak, J.: Non-uniform corrosion of steel rebar and its influence on reinforced concrete elements' reliability. Prod. Eng. Arch. **26**(2), 67–72 (2020). https://doi.org/10.30657/pea.2020.26.14
17. Krainskyi, P., Blikharskyy, Y., Khmil, R., Blikharskyy, Z.: Experimental study of the strengthening effect of reinforced concrete columns jacketed under service load level. In: MATEC Web of Conferences, vol. 183, p. 02008 (2018). https://doi.org/10.1051/matecconf/201818302008
18. Mohsem El.Sh.: Feasibility study of transversely prestressed double tee bridges. PCI J. **35**(5), 56–69 (1990)