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Assessment of Numerical Models for Live Load Distribution in a Road Slab Bridge

Janusz Hołowaty

Faculty of Civil Engineering and Architecture, West Pomeranian University of Technology, Szczecin 70-311, Poland

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Abstract: This paper presents comparison of numerical models used in an analysis of a road bridge deck. The models were adapted for computing the live load distribution coefficients in composite concrete bridge deck. The load distribution method was chosen for assessment of the usability of different numerical model in slab bridge deck analysis. The goal of the study is to determine a simplest but still accurate numerical model to estimate live load effects on composite slab bridge. In the analysis, the well-established grillage approach was adapted for representation of the bridge deck as a basic model as well as more sophisticated three-dimensional models which was supposed to better represent the real behavior of the deck under concentrated wheel loads. The bridge deck was effectively modeled using beam and shell elements. The grillage method compares well with the finite-element method. This finding is allowed to establish simplification in numerical modeling of slab bridge decks for live load effect computations.

Key words: Numerical model, bridge live load, numerical modeling, grillage method, FE analysis.

1. Introduction

Bridge decks resistance is designed or verified in expected design situations. Computer programs are extensively used in computations, but there is still some uncertainty about the final results. In some countries, there are still used simplified code-specified methods for designing new bridges or verifying existing structure [1-5]. They are simple to use by adapting distribution factor methods and for most cases produce conservative results with some exceptions. The simplified methods are refined and calibrating using numerical methods and testing [2, 3]. The traditional methods of live load distribution in bridge decks are sometimes too conservative and development of numerical methods is inevitable where a more rigorous analysis of each case is required for proper assessment of bridge deck resistance.

While preparing a schedule for a road bridge repair the problem aroused with its existing capacity [6, 7]. The bridge utilized a typical deck which had been adapted in the structure as a “non-computation” element. As the required capacity for bridges on main roads in Poland had been increased since the construction of the bridge its capacity should be verified and if not adequate, it should be increased during the strengthening works. To minimize the strengthening works undertaken structural analysis of the bridge deck should be very accurate and precise. The numerical models used in the structural assessment of the bridge deck and the results for live load distribution are presented and compared in the paper. The results of the numerical analysis can help increase the allowable traffic loads on a standard bridge deck.

The objectives of this study are to investigate the effects of numerical modeling on the live load distribution of a standard composite slab bridge and develop a more general procedure for the re-evaluation of existing bridges. Many traditionally-designed bridges or bridges with an unknown design history

Corresponding author: Janusz Hołowaty, Ph.D., assistant professor, research fields: testing and design of bridges. E-mail: jah@wp.pl.

require a more accurate determination of their true load capacities using contemporary numerical techniques. Numerical re-evaluation of bridges with a good performance may be a cost-effective methodology for bridge assessment to avoid loading restriction or strengthening. The numerical methods adapted should be both accurate and comprehensive for engineers. The use of refined numerical methods should be encouraged, as they are more accurate and offer a better description of real load distribution.

Many such bridges were constructed in the 1980s and 1990s on the Polish road network utilizing a loading class lower than that required today. Due to an increase in loading classes for bridge structures on all types of roads, the bridges constructed during that period have become substandard. The numerical approach presented may help to solve the problem with such bridges giving more sustainable and economical solutions.

The paper is organized as follows: Section 2 (the slab bridge), Section 3 (approach), Section 4 (numerical models), Section 5 (results), and Section 6 (conclusion).

2. The Slab Bridge

Opened to traffic in 1988, the bridge utilizes precast voided box girders with cast-in-place reinforced concrete overlay of 140 mm deep. Standard reinforced concrete (RC) beams of 12 m in length were used so no design computation was necessary for the deck. The concrete overlay was introduced in this type of deck to avoid disadvantages of shear-key slab decks.

The total length of the deck is 12.50 m. Composite concrete overlays is used in this bridge deck type for the enhancement of load distribution behavior and to avoid cracking in the bridge pavement. The slab deck is supported on small pile abutments of an individual design. A side view of the bridge with adjacent precast beams is shown in Fig. 1. The bridge is simply supported as are the majority of short-span bridges built at that time. The width of the bridge is 14.0 m and consists of a 7.0 m carriageways and a sidewalk. The bridge was constructed as a square structure despite being located on a transition curve of the road.

Fig. 1 Side view of the bridge before upgrading.

The bridge is located on a trunk road with a high volume of traffic reaching 10,000 vehicles per day at the time of repair. The road section of the bridge is still one of the most traffic-loaded in the Western Pomeranian Province (Poland).

After nearly 20 years of service, damage to the asphalt pavement had occurred, which required repeated repairs [6]. In addition, there was leakage through expansion joints which had suffered damage. Along with these problems, there were doubts concerning the condition of the deck waterproofing and the deck itself. Verification of the bridge concrete members gave good results. Meanwhile, higher load limits for bridge structures had been introduced to meet requirements for the increasing weight and volume of traffic in Poland. The bridge was designated for repair and the structural capacity was to be verified following the higher loading requirements.

The results of structural analysis allowed the preparation of an efficient program for bridge upgrading to be carried out during the repair works. In the upgrading program, a new reinforced concrete overlay cast in situ was added to the deck after removing the top concrete cover. The overlay profiled the deck for a new waterproof membrane and asphalt pavement. The load bearing capacity of the bridge could be quite easily increased to the highest class of traffic loading required for the trunk road. A view of the bridge deck after the reconstruction works adapted in the study is shown in Fig. 2.

3. Approach

In bridge superstructures, the most critical members are the longitudinal girders which transmit loads to the supports. In bridge evaluation, the maximum moment in the girders should be calculated and it should be lower than the girder resistance. The problem is three-dimensional and involves the complex behavior of load paths on girders in every bridge type. On bridge deck under consideration, part of the load is carried by the precast beam beneath and part transferred laterally to adjacent precast beams by a reinforced concrete overlay Fig. 2. The concrete overlay is essential for wheel load distribution on adjacent beams on the deck; no shear keys between precast beams are used.

There are many methods suggested for bridge analyses, ranging from the very simple to a sophisticated finite element approach [1-5, 7, 8]. For existing bridges, their technical condition or even the condition of the pavement on the bridge should be taken into account. Nowadays numerical methods are commonly used as they more accurately assess true resistance than traditional, sometimes outdated methods. Adaption of numerical methods gives the possibility of modeling individual elements or damages separately.

The distribution of live loads for flexure on beams in a simply supported bridge can be obtained by positioning traffic load models on the bridge so that the bending moment reaches the maximum value at midspan. For the purpose of the numerical model comparison presented in the paper, the classical numerical lateral load distribution approach is applied for the numerical analyses [3, 5]. This is accomplished with the use of influence lines for lateral live load distribution. The bridge girders are loaded at midspan with a concentrated load (Fig. 3).

The deflection of girder i due to a concentrated load on girder κ is defined as fik. The sum of the girder's

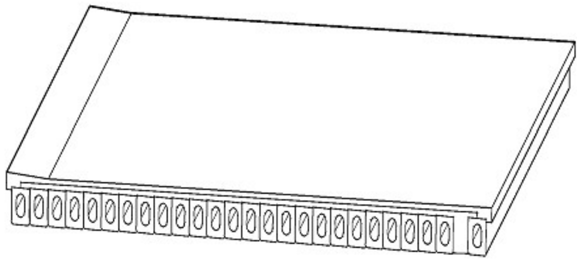

Fig. 2 Isometric view of the bridge deck.

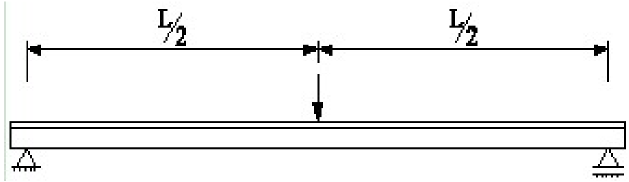

Fig. 3 Loading scheme for calculation of distribution influence lines for longitudinal girders.

deflections is fN which is the total deflection of the girder at midspan. The lateral load distribution coefficient κ is described by the formula [5, 7]:

$$\kappa_{ik} = \frac{f_{ik}}{f_N} \quad (1)$$

For a bridge with N girders, the solution requires N distribution coefficients for each girder computed according to the Eq. (1). All these coefficients are dimensionless and can be used in the same way as usual influence lines.

4. Numerical Models

The load distribution behavior of the bridge deck was evaluated by comparing the influence lines for lateral load distribution computed using different numerical models. Initially, when verifying the bridge capacity, the grillage analogy was used to model the bridge deck [1, 4, 6, 7]. The grillage analogy generally produces more accurate results than simplified bridge deck analysis methods. The results of numerical grillage analysis showed so-called "hidden" reserves of strength with the result that higher allowable loads might be taken into account. For the safety of the bridge and reasonable strengthening, more sophisticated models were also developed. In all the models, a linearly elastic behavior range was used. The section properties of the numerical elements were simply calculated using the concrete properties of the deck members, see Fig. 2.

In numerical analyses, the classical lateral load distribution method is applied [3, 5]. The computed distribution coefficients κ as influence lines for lateral load distribution are analyzed for selected bridge deck beams. Adapting the classical deflection approach for load distribution makes the computed distribution coefficients independent of the type of loading. The shapes of the load distribution influence lines allow the critical position of traffic loads to be determined.

Several models, plane and three-dimensional, were used in the bridge deck modeling. In the bridge deck cross section, the girder components, i.e. a precast beam and an over slab, were modeled as one beam member, two separate interconnected beam elements and as interconnected beam and plate (shell) elements. A general layout of the numerical elements adapted in the analyses is shown in Fig. 4. The transverse members are modeled by equivalent concrete overlay elements. In 3-D models, rigid beam elements are used to connect the cencroids of the box beams and the concrete overlay. These elements are used to model the full composite behavior of the slab bridge deck and prevent relative deformations between the concrete overlap and precast box RC beam. In two 3-D models, the rigid vertical beams are omitted and reciprocal joints are introduced (kinematic constraints). This capability is usually included in commercial software and is denoted by several terms, i.e. slave-master relationship.

In all the models, a fine mesh of elements is applied. Each precast beam is modeled by represented longitudinal beam elements, 2-D or 3-D. Transverse elements are provided with sufficient spacing for detailed analysis. Therefore, the effect of adapted meshes is not assessed in this study. In the next section, the live load distribution influence lines were compared with the critical interior and external girders.

External girders usually need special consideration as they can carry more live load moments than the interior girders. The external girder and first interior girder control the re-evaluation of the bridge capacity.

4.1 Grillage Models

Four grillage models are developed in the analyses. Two are typical plane grillage (2-D) but one lies on a horizontal plane, G in Fig. 9 and the second on a skew plane to model the existing cross fall of the deck, which is located on the horizontal transition curve of the road. The full composite action of the concrete overlay is used in calculating the properties of the longitudinal grillage members. For the transverse members, only the concrete overlay parameters were developed. The transverse elements are used to connect the centroids of composite girders. These members modeled the concrete overlay as an element of deck integrity; however, they are applied in the centroids of composite girders. The grillage model scheme of the bridge deck is shown in Fig. 5.

Two other grillage models use so-called upstand grillages. UG in Fig. 9 which are an extension of the grillage of a space frame (3-D). The mesh of downstage longitudinal elements is coincident with the precast beams and an upper mesh modeling concrete overlay is added. The upper beam elements model the concrete overlay and are applied at its central plane. There is also coincidence of the downstand and upstand longitudinal elements. The longitudinal elements are restrained reciprocally for vertical displacements (Fig. 6).

The vertical elements are used to satisfy composite behavior and prevent relative deformation. Transverse beam elements model the concrete overlay and lateral behavior of the bridge deck. The upstand grillage model is similar in discretization to the FE model (Fig. 6), but to model the top concrete overlay. Beam elements are used.

4.2 Finite Element Models

Two finite-element models are used for the deck analyses. They are upstand FE models (3-D). The precast

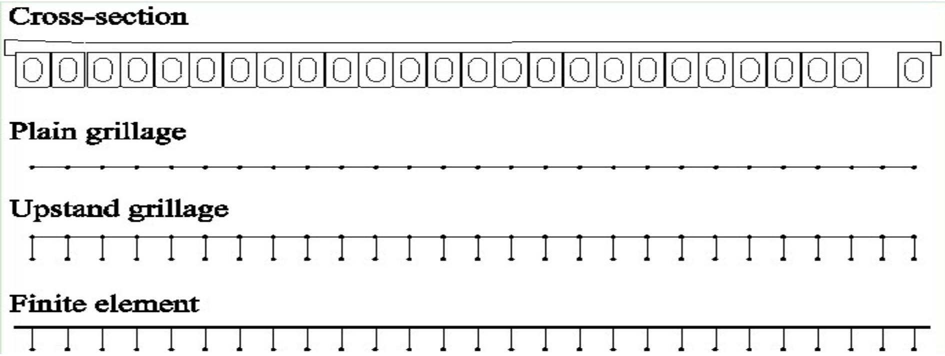

Fig. 4 Cross section of the bridge deck and equivalent plane grillage, upstand grillage and finite element models.

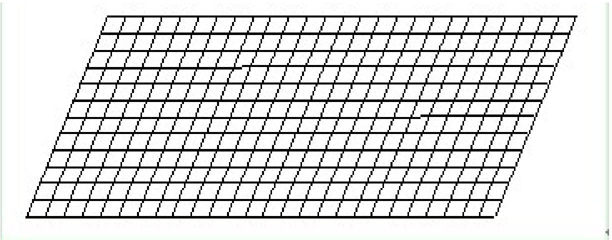

Fig. 5 Plane grillage mesh of slab bridge deck.

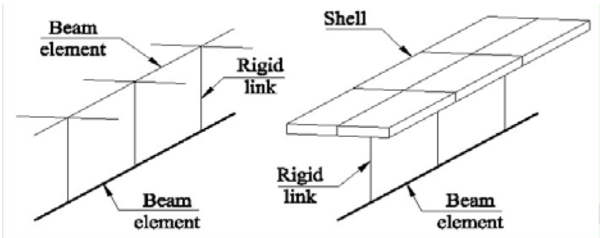

Fig. 6 Discretization of girder by upstand grillage members and finite elements (3-D models).

bridge beams are still modeled by beam elements and the concrete overlay (slab) is modeled by FE rectangular shell elements. The shell elements account for both membrane and bending behavior. The beam elements are located in the centroids of the precast beams and the shell elements are located in the centroid of the equivalent slab members. The horizontal elements at different levels in these two models are again joined by vertical ridged elements at different levels in these two models are again joined by vertical ridged elements (Fig. 6) or restrained reciprocally.

Fig. 7 shows the discretization of a 12.5 m long bridge superstructure by finite elements. A scheme of a finite element model for one girder with vertical rigid links is shown in Fig. 6. The finite element models utilize the non-composite section properties of two

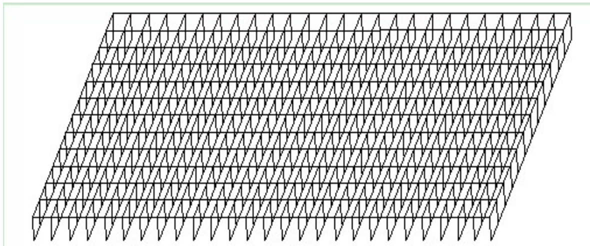

Fig. 7 Finite element mesh of slab bridge deck with vertical rigid beams used in 3-D models.

elements to model composite action by imposing rigid links or kinematic constraints between them.

4.3 Adaptability of Classical Lateral Load Distribution Approach

The comparison of results for load distribution behavior may be presented in many different ways. Usually, it uses trucks or uniform lane loading for predicting bending moment or bottom fiber stress distribution in longitudinal girders. Trucks, tandem, axles or lane load are typically included in bridge loading codes. For this study, the lateral load distribution is used in its classical approach. For comparison of the results derived from numerical models influence lines for load distribution are used. This allowed complexity, in data from the numerical analyses to be avoided.

The load distribution approach is usually well known to bridge engineers but using numerical methods require some experience and basic knowledge to model the behaviour of bridge systems.

In Fig. 8, comparisons of the results for deflection and longitudinal bending moment at midspan for plane

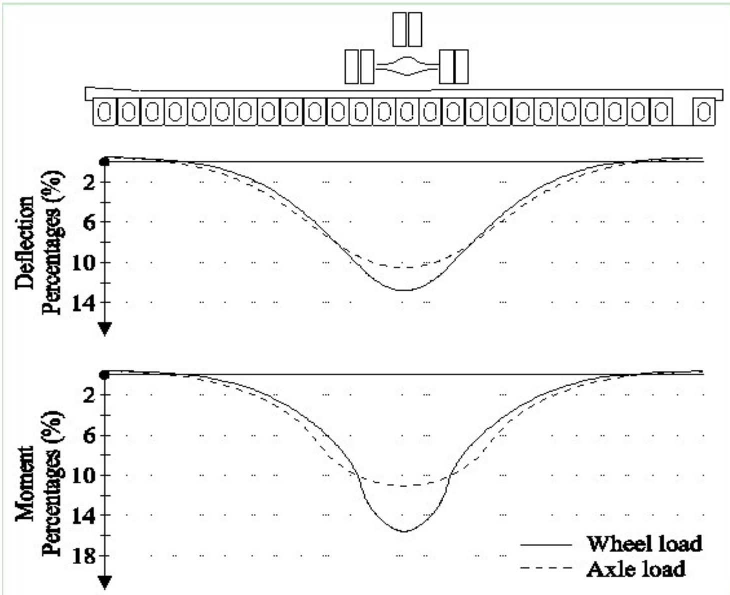

Fig. 8 Comparison of deflection and moment percentages derived from numerical analyses.

grillage are presented. The predicted values for axle load and concentrated load result in a safer maximum percentage for the point load. Therefore, the adoption of a point load to derive load distribution influence lines in the bridge deck sufficiently controls the results for live loads. The relative difference between the two approaches is below 5%, being more conservative for load distribution.

5. Results

All models achieve similitude between numerical nominal elements and the parts of the bridge deck. Grillage models are only approximation of a real slab bridge and even when used correctly there is usually some inaccuracy in them. Upstand models are more accurate however interpretation of results may be tedious for FE models. For comparison of the numerical models, the live load distribution technique was adapted in its classical form and using influence lines.

The bridge girders are loaded at midspan by vertical concentrated force which is moving from girder to girder. The nonuniformity of girder deflections in cross section indicates load distribution. The load distribution coefficients are calculated according the Eq. (1). The computed distribution coefficients as influence lines for lateral load distribution for external and internal girders of the bridge deck are presented in Fig. 9.

For the analyzed girders, the distribution coefficients agree very well. The comparison falls within the expected degree of accuracy, within 5%. It is shown that the bending moments from the grillage analyses compare very accurately with the bending moments computed from FE models. The influence on distribution of internal forces and deflections is not significant as the response of the girders is determined by flexural deformations. The high value of distribution coefficients or ordinates of influence surface for bending moments in external girder need special consideration (Figs. 9 and 10). The influence surfaces for bending moment computed for plane grillage (G) are shown in Figs. 10 and 11.

The grillage and FE analyses show consistently higher coefficients and ordinates for the exterior and the first interior girders which are located near the edge of the bridge carriageway. The external girder carries more live load than the other girders and this limits the bridge deck resistance.

All models accurately describe the flexural and shear

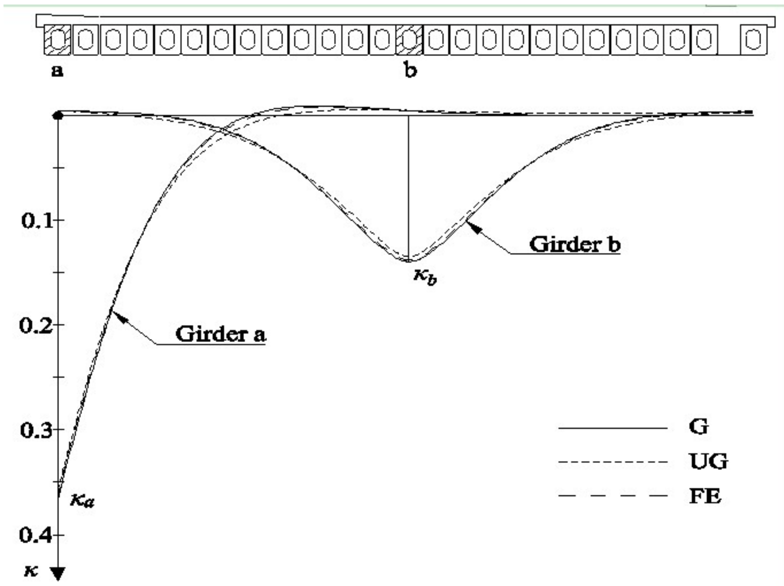

Fig. 9 Comparison of live load distribution in a composite slab bridge deck: (a) external girder, and (b) internal girder.

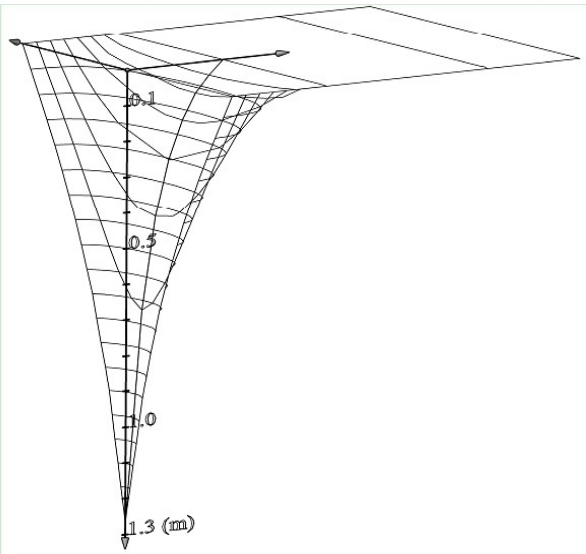

Fig. 10 Influence surface for bending moment in external girder.

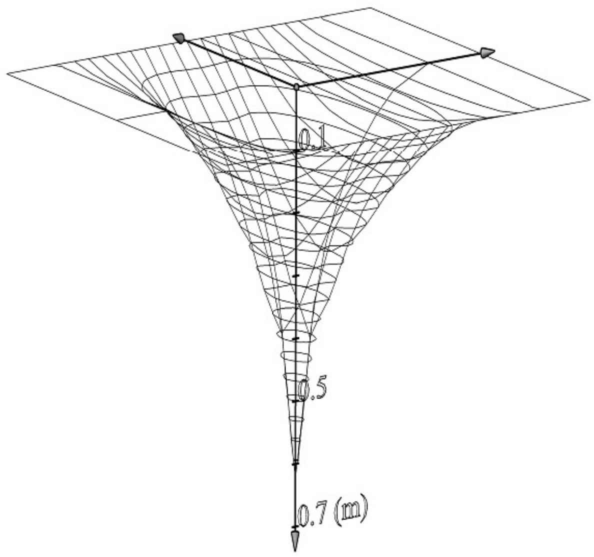

Fig. 11 Influence surface for bending moment in internal girder.

behavior of the slab bridge deck; differences in results are very small. Slab deck orthotropy is considered precisely in the plane and upstand numerical models. The careful preparation of numerical models ensured the accuracy of results, even for 2-D models.

6. Conclusions

Plane and upstand models are used for analyses of live load distribution for a concrete composite bridge deck. The upstand grillage and FE models are used to describe the behavior of the deck more accurately. For these models, different neutral axes in longitudinal and transverse section are automatically determined. In the analyses of results the classical approach of lateral load distribution is applied as a simple tool independent from loading types. The distribution coefficients are proved to be suitable for assessment of load effects in the bridge deck. Comparison of numerical models performed well for live load lateral distribution for external and internal girders.

Fig. 12 Side view of the bridge after upgrading.

The carried out numerical analyses show that for the considered bridge deck even the simple plane grillage model gives adequate results for the live load distribution. No distortion in the location of neutral axis is observed for this type of deck. The more sophisticated models prove the simplified assumptions adapted in structural assessment of the bridge.

This allows higher design loads to be taken into consideration after execution of reconstruction works. A side view of the bridge after upgrading and work to make it integral is shown in Fig. 12.

Detailed bridge deck analysis using modern software may be used to precisely evaluate the design or existing resistance. The availability of modern computer programs with more powerful computers may assist bridge engineers in performing detailed and realistic analyses of even complicated bridge decks, ensuring safety and economy.

References

[1] E.C. Hambly, Bridge Deck Behaviour, London, E&FN Spon, 1991.

[2] NCHRP, Simplified Live Load Distribution—Factor Equations, Washington, TRB report 592, 2007.

[3] J. Hołowaty, Numerical method for live load distribution in road bridges, Roads and Bridges 4 (2010) 29-46, in Polish.

[4] J. Hołowaty, Live load distribution for assessment of highway bridges in american and european codes, Structural Engineering International 22 (4) (2012) 574-578.

[5] J. Hołowaty, Numerical method for live load distribution in road bridges, in: Proceedings of the Fourth International Conference on Advances and Trends in Structural Engineering, Mechanics and Computation, 2010, pp. 425-428.

[6] J. Hołowaty, Repair of precast beam deck by making it integral, in: A. Podhorecki, A.S. Nowak (Eds.), Bridges—Tradition and Future, University Press, Bydgoszcz, Poland, 2011, pp. 127-135.

[7] J. Hołowaty, Numerical modelling of bridge decks in practical examples, in: Proceedings of the IX Polish Conference on Computer Methods in Mechanics, 1993, pp. 331-336.

[8] E.J. O'Brien, D.L. Keogh, Bridge Deck Analysis, E&FN Spon, London, 1999.