ARCHITECTURE CIVIL ENGINEERING ENVIRONMENT
The Silesian University of Technology
No. 3/2021

doi: 10.21307/ACEE-2021-023

A PROPOSAL TO FACILITATE MANDATORY BRIDGE LOAD TESTS WITH ARTIFICIAL NEURAL NETWORK ANALYSES USING A DIGITAL DATA AGGREGATION PLATFORM

Piotr OWERKO [a*], Jerzy KAŁUŻA [b], Marek WAZOWSKI [c]

[a] Assistant Prof.; PhD, Faculty of Materials, Civil and Environmental Engineering, University of Bielsko-Biala, Bielsko-Biala, Poland
*E-mail address: *powerko@ath.bielsko.pl*

[b] MSc; Aspekt Laboratorium Sp. z o.o., ul. Chopina 96, 43-600 Jaworzno, Poland

[c] PhD; Aspekt Laboratorium Sp. z o.o., ul. Chopina 96, 43-600 Jaworzno, Poland

Received: 21.05.2021; Revised: 29.06.2021; Accepted: 03.07.2021

Abstract
The paper presents an innovative concept of digital aggregation of data related to mandatory in-situ load tests of bridge structures. The proposed approach allows to manage various types of information regarding those experiments, in a way which is consistent with current good practises in BIM technology and digitalisation of construction industry. The proposed web platform will allow for vast improvements in decision-making process regarding admission of a given bridge for service, in proper analyses and even predictions of bridges mechanical response. Initial architecture of the system is introduced along with an appropriate literature review and the identification of key actors and their roles in the described information management process. To highlight the potential of the solution, two examples are shown. In both cases key advantages of digital aggregation are emphasised: the possibility to learn from previous analogical in-situ experiments, and the possibility to utilise modern machine learning algorithms and state-of-the-art open-source solutions.

Keywords: **Bridge load tests; TensorFlow; Neural networks; API, BIM, Digitalization.**

1. INTRODUCTION

In the last few decades, a very large number of load tests of engineering structures has been performed in central Europe. The main cause of this is rapid development of the transportation infrastructure in the region and the fact that such in-situ tests are recommended [1] or even required as mandatory in numerous countries – e.g. in Slovakia, Spain, Italy and Poland [2, 3, 4]. These measurements are performed at different stages in the life cycle of the structure:

a) during the construction phase – e.g. load testing of foundation piles [5],
b) directly before admission to service – as mandatory static and dynamic test loading of road and rail bridges [2, 6, 7]
c) during service life of the bridge – e.g. when facing a renovation decision, as part of an expert opinion on the technical condition or when it is necessary to increase the load capacity of the structure due to increasing operational requirements [8, 9].

Out of the above mentioned stages, the most frequent are mandatory proof load tests. It can be estimated with considerable certainty that only in Poland itself, the total number of such experiments to date is greater than 10,000. So far, all these data are fragmented and archived within the resources and archives of individual units/laboratories that are authorized in a given country. Individual results are transferred to the owners (public bridge investors), but usually to a very limited extent and in an archaic way. There are also no strict universal guidelines as to the method and scope of this archiving. This mainly depends on the management strategy adopted in the individual field laboratories dealing with the load tests of the bridges. Unfortunately, there is also no strict strategy for transferring this data to the public bridge owners/managers that would comply with good practices of BIM/BriM (Bridge Information Modelling) [10, 11]. There is also no direct support for infrastructure managers of the road and rail systems, respecting the proper conduct of the information management process (IMP), in accordance with the good practices of AM (asset management) strategies included in e.g. [12, 13] and recent advances in the digitization of the transport construction industry in Central Europe [14, 15].

Currently, the information exchanged in the aspect of bridge load testing are also not properly included in the risk management strategy of the public bridge owners. They are also not present as adequate components of the information management process, for example in the form of PMS (pavement management systems), which are often supported by CMMS (computer-managed maintenance systems) [16]. According to the group of standards [10], it is necessary to ensure possible lossless transfer of information between the particular phases of the structures life cycle and between the particular actors – e.g. between the contractor and the bridge facility manager.

This group of relevant information regarding bridge load testing should not be limited to span deflections or vibrations frequencies only. The entire spectrum of related data should be present and properly exchanged, including i.e. material, time, survey, mechanical, geographic, meteorological and many other data, which can be very valuable in the future process of information management regarding road or rail bridge structures. In BIM processes, it is also improper to operate in isolation from other industries and domains. Experience, data and information from the construction and testing of similar bridge objects should be used.

Therefore, most of the information related to the described load tests should always be included in two apparently separate information areas.

(I) In the “data drop” package on the edge of the construction phase, accompanied by the project information model (PIM) and the projects operational phase, accompanied by the asset information model (AIM) in accordance with the organization’s information requirements (OIR), management requirements (AIR), functional requirements (FIR), employers requirements (EIR) with related documents specified by it – as part of a specific BIM infrastructure undertaking: e.g. Master Information Delivery Plan (MIDP), all in accordance with good practices defined in [17].

(II) In the collective, national, heterogeneous database system aggregating all valid information regarding mandatory bridge load tests – which is the focal aspect of this study.

2. PURPOSEFULNESS OF BRIDGE LOAD TESTS

From the formal point of view, the main task of the mandatory load tests is an attempt to confirm the correctness of the structure’s mechanical response and to support the decision on the acceptance of the object for service. However, taking into account the set of good practices contained in the previously cited sources, the main purpose of the load tests should be formulated much more broadly. Generally speaking – there should be an increase in the degree of saturation and maturity of the information model (Digital Twin) of the object and thus improvement of the quality of decision-making processes concerning it. Therefore at least these several aspects should be closely investigated and assessed:

- supports settlements and bearing deformations control [18],
- global stiffness of the structure [19],
- control of the occurrence of local abnormalities (e.g. mutual collisions of loose hangers of arch bridges in dynamic tests), cracks, local detachments of concrete cover etc. [20, 21, 22],
- validation of the assumptions of numerical FE models analyzed both in the longitudinal and transverse directions as well as in the context of the dynamic response of the model / calibration of the FEM model – replacement of the FEM model class [23],
- load capacity validation [9],
- reliability validation [24],
- fatigue reliability validation [25],
- initial calibration of the SHM system [26], including the creation of an appropriate reference point and determination of alarm thresholds,

– reference base for subsequent measurements [27].

It should, however, be emphasized, that all of the above objectives can be achieved much more reliably in the view of the existence and possibility of insight into the statistics from analogous results of the mechanical response of similar bridges that have been studied in the past. This applies in particular to selected typical bridges presented in [28]. Importantly, collection of information about these bridges aggregated this way enable their representation and management in accordance with the requirements of modern standards [12, 17].

3. PROPOSAL OF A DIGITAL DATABASE OF BRIDGE LOAD TESTS

Taking into consideration the above mentioned remarks, the main proposal of this study is to create a collective, digital databases containing all crucial information regarding the conducted mandatory load tests in countries where such experiments are obligatory (e.g. Slovakia, Spain, Italy, Poland). The database in given region would be created on the basis of digital resources of all the largest load testing laboratories in region. In this paper data sets from Poland are highlighted as exemplary. Such database will consist of coupled heterogeneous data containers (SQL databases, data in the form of time series, documents) concerning the mechanical response of the structure, geographic data, time data, material data and many others. Not all data types are envisioned as mandatorily provided by all laboratories, however, greater variety of information containers has larger potential for future application. Access to this collective data base will be available – on properly defined terms – to both the managers of the transport infrastructure in Poland and all the actors of individual transportation construction undertakings. This will also require appropriate formal and legal preparation in the projects' post-pilot application phase, in particular on the part of public administrators (however, it is not the purpose of this study to discuss this aspect). The database and appropriately addressed

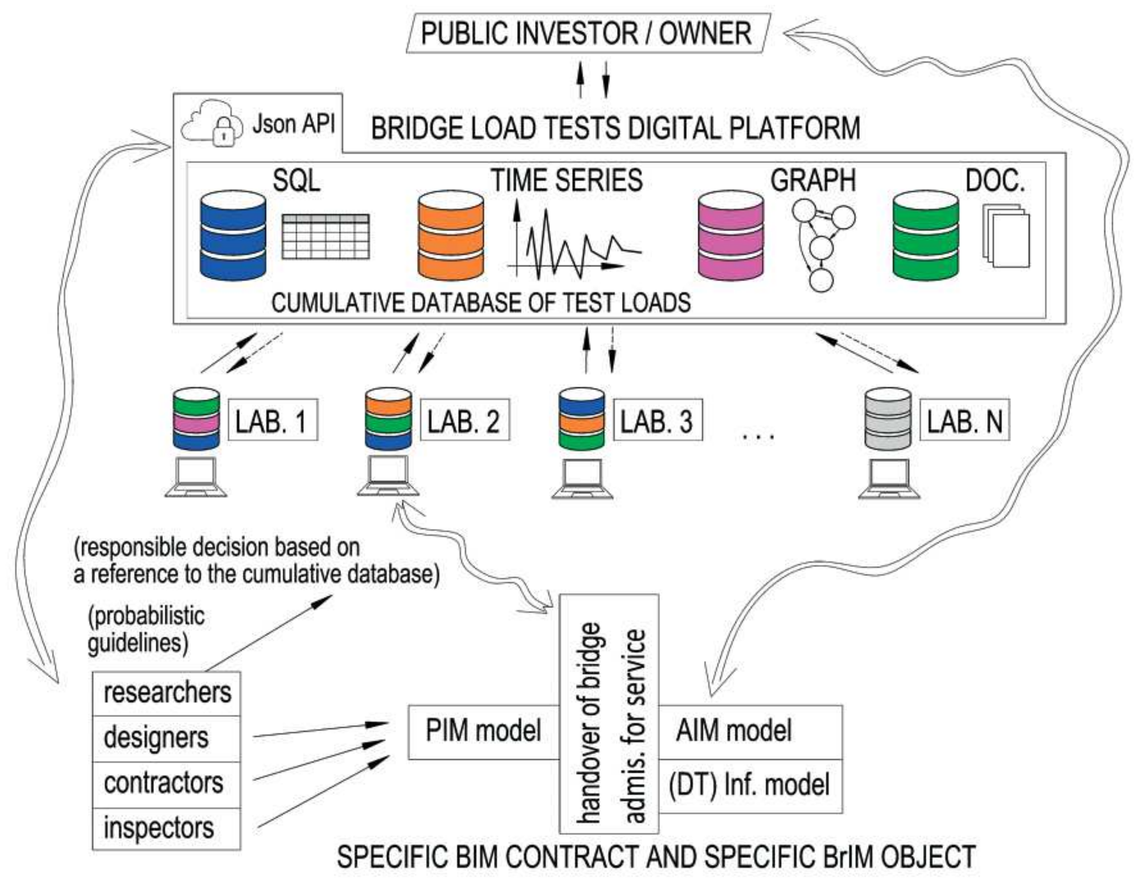

Figure 1.
Simplfied sketch of proposed digital platform for bridge load tests information management

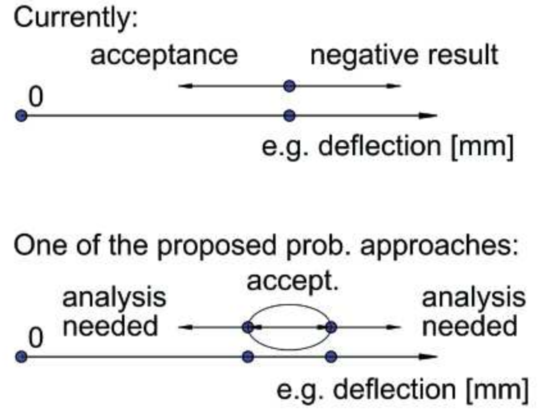

Figure 2.
Simplfied sketch of proposed modifications in the bridge approval criterion [32]

data inquiries (through API on a digital platform) may turn out to be key in the process of making the correct decision on approving a given bridge for service or initiating possible repair programs, implementing additional monitoring [29], and as to the required method and scope of updating the information model (digital twin DT) of a given bridge. Experts performing the load tests will no longer rely solely on the designer's analytical finite element (FE) model or their own archives, but will have full statistics of the mechanical response of analogous objects at their disposal, with the complete context of other data types. Therefore, the decision-making process and hence the process of saturating the model included in the BrIM strategy with information will be more responsible and valuable. Fig. 1 shows a collective infographic which in a simplified and intuitive way shows selected aspects of the proposed database system and appropriate connections.

Importantly, the authors' proposal envisions a process that is in line with the standards and trends of modern research literature [8, 27, 30, 31], in which it is clearly emphasized that it is worth enriching the traditional deterministic approach to the load test designs through a probabilistic approach and analysis of large amounts of data (so-called "Big Data"). Single, usually uncalibrated deterministic values are then replaced with appropriate - probabilistically defined – intervals of the expected values of the mechanical response of the structure based on a reliable analysis of sensitivity and uncertainty [32], (Fig. 2). It is worth to note that Fig. 2 presents very simplified version of the above mentioned procedure, thus the reader is encouraged to read the source study [32].

4. SIMPLIFIED EXAMPLES OF THE USE OF ARTIFICIAL NEURAL NETWORKS TO ANALYZE AND PREDICT THE LOAD TESTS RESULTS OF TYPICAL BRIDGES

Two illustrative examples were used to highlight the application potential of artificial neural networks in the analysis and interpretation of the in-situ bridge load tests. Both examples concern typical, two-girder, two-span, post-tensioned road viaducts (Fig. 3). It is worth to emphasize that it is not the intention of the authors to eliminate in-situ test loads; on the contrary, neural networks are to contribute to the improvement of the quality of inference based on these tests.

Usually, a large amount of data is required to properly train and validate the performance of deep neural networks. In the following, illustrative examples, an small excerpt from the database of the accredited testing laboratory of Aspekt® Laboratorium Sp. z.o.o was used. For each of the representative objects presented in Fig. 3, 73 data types were archived. These are, for example, geometric data (e.g. theoretical spans, spacing of girders, cross-sectional characteristics, etc.), geographic, material (e.g. incisal modulus of concrete elasticity), meteorological data, regarding the method and quality of measurement, results (e.g. displacements, deformations, settlements, vibration and damping parameters) and others.

Due to the illustrative nature of the provided examples, two basic limitations to simplify the analysis have been adopted. Firstly, only 11 tested objects of the type shown in Fig. 3 and 11 data sets with appropriate load-tests results (and related data) were selected for training the neural networks. This number results from the availability of relevant data in the pilot (preliminary) stage of the project. Due to such a limited number of training examples, the validation set was not built (all examples were used to optimize the network weights). Secondly, the scope of the decision-making process regarding the types of data saturating a given perceptron has been arbitrarily limited to a dozen key parameters based on analyzes, e.g. correlation and sensitivity after rescaling the input data [33] and also based on the authors extensive experience in this field.

The purpose of the neural networks in the example "A" is to predict the average deflection of the girders in future stress tests of analogous viaducts. On the other hand, the goal of neural networks in the example "B" is to find the expected percentage difference in the displacements calculated theoretically from the

Figure 3.
Exemplary typical bridge under test loading

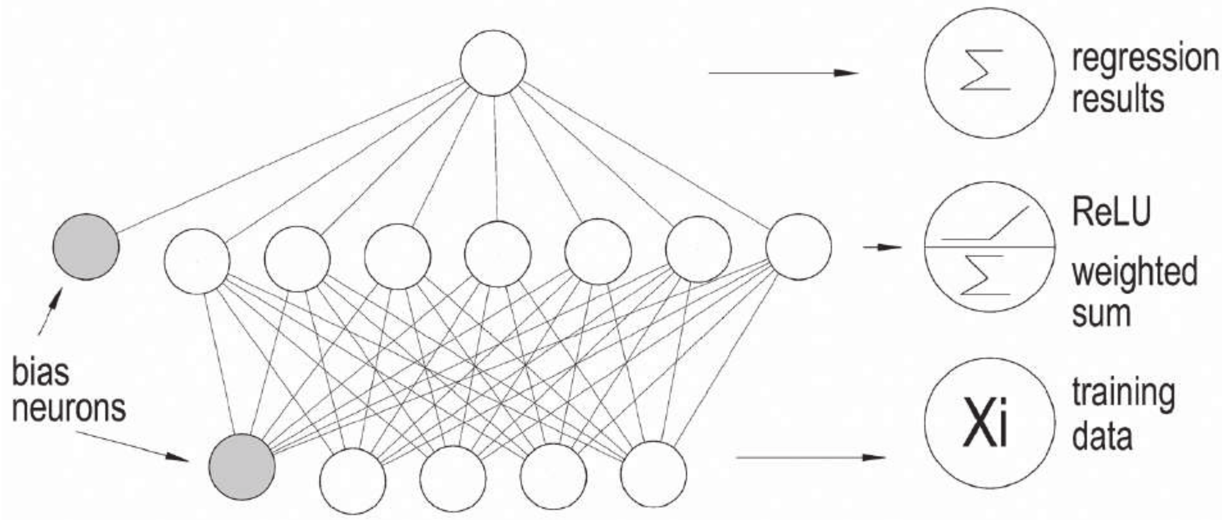

Figure 4.
Regression perceptron of 4-7-1 architecture

FE model, and those that will be obtained in the in-situ measurements. Both examples refer to the static part of the tests, and in both, three architectures of neural networks were analyzed: the 7-7-1, 7-9-1 and the 7-5-4-1. These numbers denote respectively: the number of batch units (representing input/training data), the number of neurons in a given hidden layer (layers "in between" the input and output) and the number of neurons in the output layer (regression results in this study), not including bias neurons. To better understand this notation, a sketch of the 4-7-1 perceptron is provided in Fig. 4, along with two bias neurons that always "send" a value of 1.0 (gray-filled neurons).

Two key hyperparameters: the number of layers and the number of neurons in a given hidden layer (and thus the given network architecture), were chosen on the basis of two good practices introduced e.g. in [33]. (1) For most problems, especially with a limited number of training examples and parameters, it is good practice to start with one hidden layer. (2) The second principle was that the first hidden layer should be larger than the rest (adopted in the 7-5-4-1 architecture).

All perceptrons in hidden layers use the so-called "Rectified Linear Unit" (ReLU) activation function [33]:

$$ReLU(z)=\max(0,z) \tag{1}$$

Due to the regressive nature of the network, the activation function in the output layer was omitted. After the analyzes and taking into account the preliminary nature of the examples, to predict the average deflection of the girders in static tests (example "A"), training parameters were selected in the form of: (1) directly loaded span length, (2) skew value, (3) axial moment inertia of the girders, (4) the width of the road, (5, 6) the widths of the sidewalks, (7) the theo-

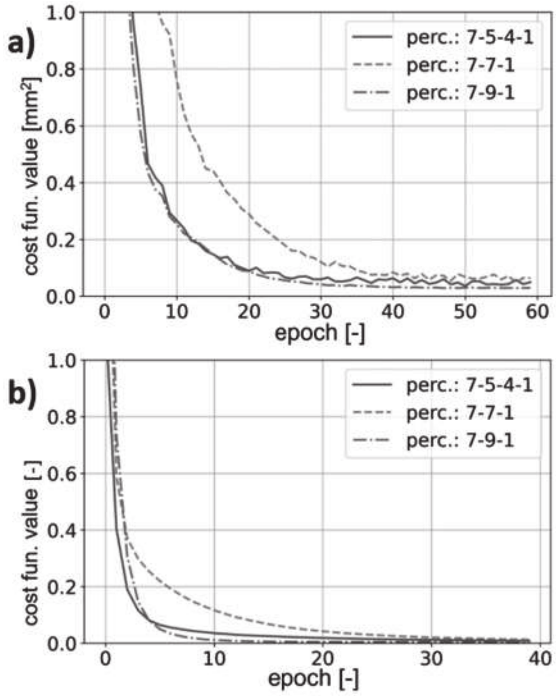

Figure 5.
Cost function values in each training epoch; in regard to: a) the example "A"; b) the example "B"

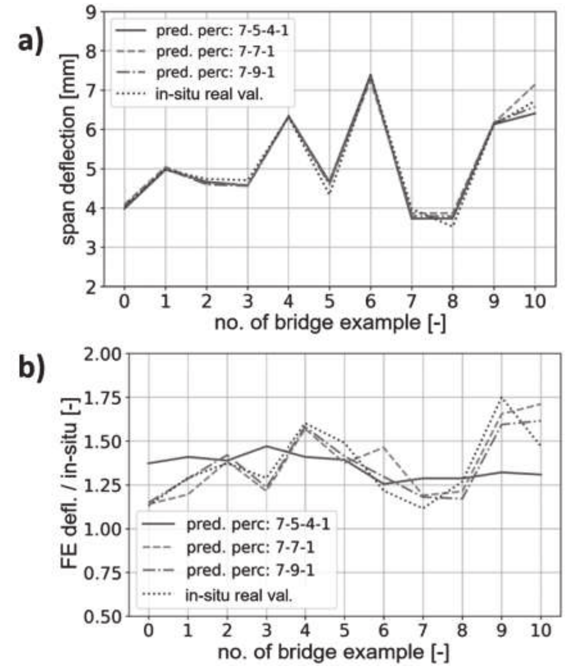

Figure 6.
Comparison of the predictive effectiveness of perceptrons in regard to:
a) the example "A"; b) the example "B"

retical modulus of elasticity of the concrete girders. In the example "B" – regarding the expected differences between the actual measurements and the theoretical FE analysis, parameter No. (7) was replaced with the result of the maximum theoretical deflection of the directly loaded span from the numerical analyzes included in the respective load test designs. It should be emphasized once again that the target number of training parameters (including calibration data from the construction site), and thus the complexity of the architecture of neural networks, will be significantly deepened in the face of the proposed cumulative database and digital platform (Fig. 1). The examples presented here are only intended to illustrate the potential of this approach. Therefore, the process of training neural networks was based on the most basic algorithm of stochastic gradient descent (SGD) with the procedure of backpropagation. This technique is explained step by step in the educational publication of the first author [34]. All 6 perceptrons – 3 in the example "A" and 3 in the example "B", have been trained based on the TensorFlow scientific Python 3 module with the implementation of the Keras [35] application programming interface.

5. RESULTS OF THE NEURAL NETWORKS APPLICATION

In case of example "A" (deflection prediction), the training process converged after a maximum of 60 learning epochs in all the three applied perceptron types (Fig. 5a). The term "epoch" is explained in e.g. [24] (and denotes one set of singular iterations through all training samples). Correct regression of the expected in-situ deflection quotient to the theoretical deflection from the appropriate numerical models (example "B") required a maximum of 40 learning epochs (Fig. 5b). The convergence criterion was identified as fulfilled if the approximation of the cost function values (at least six epochs) with the first degree polynomial returned the value of the slope coefficient lower than 0.2%.

As shown in Fig. 5a and 5b, the most efficient process of searching for the optimal network weights took place in the case of the 7-9-1 perceptron and the network with two hidden layers: 7-5-4-1. Nevertheless, regardless of the network hiperparameters, the learning curves should be initially identified as correct. The effect of training all six perceptrons is to obtain a matrix of optimally matched weights for each network, minimizing the global cost function, selected in the form of mean squared error. Weights are numerical values assigned to each of the connections between neurons, including bias neurons.

In the second step of computations – on the basis of the obtained set of optimal weight matrices – the predictions of each network with respect to all bridge structures were calculated and compared with the actual in-situ results. The training examples were therefore then treated as a separate validation set - so in this analysis the values of the network weights were constant (taken from previous step). The individual perceptrons were treated as optimized (already "trained"), and the examples collected from the in-situ experiments as not yet carried out (for which the mechanical response of the structure should be predicted). As shown in Fig. 6, the results of comparing the described predictions to the in-situ measured values are very promising.

It is worth emphasizing that for proper assessment of the trained neural networks, results from independent validation examples that were not part of the training set are needed. Such a set of validation data will be created in the face of the implementation of the authors' proposal to build a collective database system and appropriate web platform (Fig. 1). Nevertheless, already at the present - early - stage of development of the predictive models, promising relationships can be noticed. The comparison in Fig. 6a shows that based on the optimized weight parameters of individual networks, calculations of the predicted average deflections of the girders are very similar to the results of in-situ measurements. The maximum prediction error concerns the simplest 7-7-1 perceptron and does not exceed 7%. In terms of estimating the quotient of theoretical FE deflection to the in-situ deflection, the greatest comparative discrepancies were obtained in relation to the perceptron with two hidden layers (7-5-4-1). The smallest differences were obtained with the use of the 7-9-1 neural network, which turned out to be effective in both analyzed aspects. Studying Fig. 6a and 6b, it can be seen that the broken line representing the results of the 7-9-1 network is very similar in shape to the in-situ results. However, models with a greater number of hidden layers should not be disqualified, especially in the planned, future analyzes based on a significantly larger set of data and training parameters.

6. CONCLUSIONS

A few decades ago, hardly anyone predicted that the data from the construction of engineering structures, e.g. in the form of photographs of concrete cracks, would be so valuable. Today – in the era of implementing digital systems supporting the engineer's decision-making process based on digital data (the so-called "data-driven approach") and deep learning algorithms – collections of such photographs are used by virtually all reputable research units dealing with the problems of inspection of reinforced concrete structures.

A similar sets of data, with perhaps even greater application potential, are – according to the authors – the archives of the load testing laboratories in numerous countries where such experiments are obligatory. For example in Poland, there is probably over 10,000 such relevant data sets and thus information packages on bridge structures. This data should be collected and used in a manner consistent with modern Bridge Information Management (BrIM) requirements. Therefore, the main goal of this study was to present a proposal for the construction of a collective, digital, relational database of the load tests of typical bridges. In order to make this vision a reality, cooperation between the management entities (public bridge owners in given country) and all accredited load testing laboratories in given region is needed. The database will allow to significantly modernize the diagnostic process related to the acceptance of a given bridge based on the in-situ load tests due to:

- the possibility of a reliable reference of new results to wide, multi-sample, multi-criteria statistics from the results of analogous objects,
- deviation from the current practice of making acceptance decisions based solely on the often uncalibrated FEM models, in favor of multi-criteria analysis, including the use of deep learning,
- opening the possibility of enriching analyzes with modern probabilistic and reliability processes and not limiting the approach to the deterministic tools only,
- enabling reliable inference about the calibration of numerical models in many aspects (not only in terms of global stiffness correction),
- the possibility of building and developing probabilistic random fields and optimization analyzes of the expected mechanical response of a given bridge in its life cycle, along with data integration for the calibration of structural health monitoring

systems,

– improving the quality of the decision making in the aspect of admission to service / for ordering repetition of a given load test / for introduction of additional structural health monitoring / for introduction of structural recovery programs,
– enabling the correct update of the information model (DT –) of a given bridge in the BIM methodology.

In order to demonstrate the potential of the proposed approach, two illustrative examples of the implementation of deep learning algorithms were used. Both examples were limited to predicting a static mechanical response of bridges of the selected type. In both examples, three neural network architectures were used. In the first example, in which the average deflection of the girders was predicted, the error of results did not exceeded 7% of the actual in-situ deflections. Larger discrepancies were noted in the second example, which concerned the prediction of the in-situ deflection ratio to the theoretical deflection from the FEM model. However, only one of three perceptrons (with two hidden layers) returned unsatisfactory results. This is understandable, considering the limited number of learning examples in the presented computations. Nevertheless, with respect to simpler network architectures, especially the 7-9-1 system, the obtained results were very promising in both analyzed aspects of the prediction. The observations confirmed the legitimacy of conducting further research in the aspect of application of machine learning algorithms in the assessment of the bridge load tests results and consequently, the construction of a comprehensive, on-line, digital database. For this to be possible, it is necessary to aggregate and build an appropriate website with server support and a secure Application Programming Interface (API) for users and managers saturating the database in the future, in accordance with good practices of digitization of the infrastructure segment.

REFERENCES

[1] GDDKiA, Zarządzenie Nr 35 Generalnego Dyrektora Dróg Krajowych i Autostrad z dnia 12 sierpnia 2008 r. w sprawie wprowadzenia zaleceń dotyczących wykonywania badań pod próbnym obciążeniem drogowym obiektów mostowych (Regulation No. 35 of the General Director for National Roads and Motorways of 12 August 2008 on the introduction of recommendations for the performance of tests under road load test of bridges). GDDKiA, 2008. [Online]. Available: https://www.gddkia.gov.pl/userfiles/articles/z/zarzadzenia-generalnego-dyrektor_6335//documents/35z.pdf

[2] M. Łagoda. (2013). Potrzeba wykonywania badań konstrukcji mostowych pod próbnym obciążeniem statycznym i dynamicznym [The need to perform static and dynamic bridge load tests], presented at the Wroclaw bridge days seminar, Wroclaw, Poland, Nov. 20, 2013. [Online]. Available: https://www.google.pl/url?sa=t&rct=j&q=&esrc=s&source=web&cd=9&ved=0ahUKEwjn08G3y_rZAhVLXCwKHVnvABUQFghdMAg&url=http%3A%2F%2Fwdm.pwr.wroc.pl%2Fsciagnij_plik%2Fpobierz%2Fwdm_2013_program_szczegolowy.pdf&usg=AOvVaw2x3G1r_-KCj3S9b4-pTv6U

[3] PN-S-10040. (1999). Obiekty mostowe: konstrukcje betonowe, żelbetowe i sprężone; Wymagania i badania. [Bridges: concrete, reinforced concrete, prestressed concrete structures; Requirements and testing.]. Polish Committee for Standardization, 1999. [Online]. Available: http://sklep.pkn.pl/pn-s-10040-1999p.html

[4] PN-S-10050. (1989). Obiekty mostowe, konktrukcje stalowe; Wymagania i badania. [Bridges, steel structures; Requirements and testing.]. Polish Committee for Standardization, 1989. [Online]. Available: http://sklep.pkn.pl/pn-s-10050-1989p.html

[5] J. Kania and K. Sorensen. (2018). A Static Pile Load Test on a Bored Pile Instrumented with Distributed Fibre Optic Sensors, Jun. 2018.

[6] P. Owerko, K. Winkelmann, and J. Górski. (Jul. 2020). Application of probabilistic tools to extend load test design of bridges prior to opening, *Structure and Infrastructure Engineering, 16*(7), 931–948, doi: 10.1080/15732479.2019.1676790.

[7] P. Kuras, Ł. Ortyl, T. Owerko, M. Salamak, and P. Łaziński. (Jan. 2020). GB-SAR in the Diagnosis of Critical City Infrastructure – A Case Study of a Load Test on the Long Tram Extradosed Bridge, *Remote Sensing, 12*(20), Art. no. 20, doi: 10.3390/rs12203361.

[8] E. O. L. Lantsoght, C. van der Veen, A. de Boer, and D. A. Hordijk. (Nov. 2017). State-of-the-art on load testing of concrete bridges, *Engineering Structures*, 150, 231–241, doi: 10.1016/j.engstruct.2017.07.050.

[9] E. O. L. Lantsoght, C. van der Veen, D. A. Hordijk, and A. de Boer. (Dec. 2017). Development of recommendations for proof load testing of reinforced concrete slab bridges, *Engineering Structures*, 152, 202–210, doi: 10.1016/j.engstruct.2017.09.018.

[10] PN-EN ISO 19650-1:2019-02. PKN, Feb. 01, 2019. [Online]. Available: https://sklep.pkn.pl/pn-en-iso-19650-1-2019-02e.html

[11] R. Bednarczyk et al.. (2020). BIM Standard PL. PZPB, [Online]. Available: https://www.uzp.gov.pl/__data/assets/pdf_file/0024/43449/BIM-Standard-wersja-opublikowana-2.0.pdf

[12] ISO 55000:2014 Asset management — Overview, principles and terminology̓. Technical Committee: ISO/TC 251 Asset management, Jan. 2014. [Online]. Available: https://www.iso.org/standard/55088.html

[13] T. W. Kang and C. H. Hong. (Jun. 2015). A study on software architecture for effective BIM/GIS-based facility management data integration, *Automation in Construction*, 54, 25–38. doi: 10.1016/j.autcon.2015.03.019.

[14] Podpisano umowę na obwodnicę Zatora. Rusza projekt pilotażowy BIM: Generalna Dyrekcja Dróg Krajowych i Autostrad – Serwis informacyjny (A contract was signed for the bypass of Zator. The BIM pilot project is launched: General Directorate for National Roads and Motorways – Information service). https://www.gddkia.gov.pl/pl/a/36450/Podpisano-umowe-na-obwodnice-Zatora-Rusza-projekt-pilotazowy-BIM (accessed Apr. 19, 2021).

[15] S. Vitásek and P. Matějka. (Sep. 2017). Utilization of BIM for automation of quantity takeoffs and cost estimation in transport infrastructure construction projects in the Czech Republic, *IOP Conf. Ser.: Mater. Sci. Eng*., 236, 012110, doi: 10.1088/1757-899X/236/1/012110.

[16] S. Guerra de Oliveira, A. Tibaut, and G. Dell'Acqua. (2020). Airport Pavement Management Systems: An Open BIM Approach, 450–459. doi: 10.1007/978-3-030-29779-4_44.

[17] ISO 19650-3:2020. Technical Committee: ISO/TC 59/SC 13 Organization and digitization of information about buildings and civil engineering works, including building information modelling (BIM). Accessed: Apr. 19, 2021. [Online]. Available: https://www.iso.org/cms/render/live/en/sites/isoorg/contents/data/standard/07/51/75109.html

[18] L. Nittmannová and M. Magura. (2016). Experimental Verification of Elastomeric Bearings According to STN EN 1337-3, *Procedia Engineering*, 156, 280–287, doi: 10.1016/j.proeng.2016.08.298.

[19] P. Łaziński. (2009). Procedura modelowania obiektów rzeczywistych w postaci pewnego typu konktrukcji mostowych [Procedure of modeling real objects in the form of a certain type of bridge structures]. Gliwice, Poland: Silesian University of Technology, [Online]. Available: http://delibra.bg.polsl.pl/Content/607/R-4601_JG.pdf

[20] P. Owerko. (Sep. 2016). Wybrane problemy przy montażu osłonek i splotów sprężających w kablobetonowych obiektach mostowych (Selected problems in the assembly of sheaths and prestressing strands in post-tensioned concrete Bridges), *Inżynieria i Budownictwo*, 9, 477–479.

[21] P. Owerko and Ł. Ortyl. (2013). GPR identification of prestressing tendons in areas with high density of ordinary reinforcement, 13th International Multidisciplinary Scientific GeoConferences, science and technologies in geology, exploration and mining. 2, 771–778, doi:10.5593/SGEM2013/BA1.V2/S05.012.

[22] P. Owerko and T. Owerko. (2020). Novel approach to inspections of as-built reinforcement in incrementally launched bridges by means of computer vision based point cloud data. *IEEE Sensors Journal*, 1–1, doi: 10.1109/JSEN.2020.3020132.

[23] J. Bień, M. Kużawa, and T. Kamiński. (Sep. 2015). Validation of numerical models of concrete box bridges based on load test results, *Archives of Civil and Mechanical Engineering, 15*(4), 1046–1060, doi: 10.1016/j.acme.2015.05.007.

[24] A. S. Nowak and T. Tharmabala. (Oct. 1988). Bridge Reliability Evaluation Using Load Tests, *Journal of Structural Engineering, 114*(10), 2268–2279, doi: 10.1061/(ASCE)0733-9445(1988)114:10(2268).

[25] T. Guo, D. M. Frangopol, and Y. Chen. (Dec. 2012). Fatigue reliability assessment of steel bridge details integrating weigh-in-motion data and probabilistic finite element analysis, *Computers & Structures*, 112–113, 245–257. doi: 10.1016/j.compstruc.2012.09.002.

[26] Z. Zong, X. Lin, and J. Niu. (Aug. 2015). Finite element model validation of bridge based on structural health monitoring—Part I: Response surface-based finite element model updating, *Journal of Traffic and Transportation Engineering (English Edition), 2*(4), 258–278, Aug. 2015, doi: 10.1016/j.jtte.2015.06.001.

[27] P. Owerko and K. Winkelmann. (2020). Improving the Procedure of Probabilistic Load Testing Design of Typical Bridges Based on Structural Response Similarities, *Archives of Civil Engineering, LXVI*(4), 325–342, 2020, doi: 10.24425/ACE.2020.135224.

[28] T. Siwowski, E. Michalak, D. Kaleta, E. Reizer, D. Macheta, and i inni. (Aug. 2018). Katalog typowych konstrukcji drogowych obiektów mostowych i przepustów' (Catalog of typical road structures, bridges and culverts). Ministerstwo Infrastruktury, [Online]. Available: https://www.gov.pl/documents/905843/1047987/C1_Katalog_typowych_drogowych_obiektow_-mostowych_i_przepust%C3%B3w.pdf/9be9e680-403e-75a4-7a10-4da285eb66fd

[29] A. G. Mohapatra, A. Khanna, D. Gupta, M. Mohanty, and V. H. C. de Albuquerque. (2020). An experimental approach to evaluate machine learning models for the estimation of load distribution on suspension bridge using FBG sensors and IoT, Computational Intelligence, n/a, no. n/a, doi: 10.1111/coin.12406.

[30] H.-N. Cho, Y.-M. Choi, and B.-C. Sho. (Nov. 1998). Field load testing and reliability-based integrity assessment of segmental PC box girder bridges before opening to traffic, *Engineering Structures – ENG STRUCT*, 20, 948–956, doi: 10.1016/S0141-0296(97)00188-0.

[31] A. S. Nowak and T. Cho. (Dec. 2007). Prediction of the combination of failure modes for an arch bridge system, *Journal of Constructional Steel Research, 63*(12), 1561–1569, doi: 10.1016/j.jcsr.2007.05.004.

[32] P. Owerko, K. Winkelmann, and J. Górski. (Oct. 2019). Application of probabilistic tools to extend load test design of bridges prior to opening, *Structure and Infrastructure Engineering* [Article in Press], doi: 10.1080/15732479.2019.1676790.

[33] A. Géron. (2019). Hands-On Machine Learning with Scikit-Learn, Keras, and TensorFlow: Concepts, Tools, and Techniques to Build Intelligent Systems, 2nd edition. Sebastopol, CA: O'Reilly Media.

[34] piotrowerko – Overview, GitHub. https://github.com/piotrowerko (accessed Apr. 20, 2021).

[35] Module: tf.keras | TensorFlow Core v2.4.1, TensorFlow. https://www.tensorflow.org/api_docs/python/tf/keras?hl=pl (accessed Apr. 20, 2021).