STRUCTURAL MONITORING OF EXPERIMENTAL TIMBER-CONCRETE COMPOSITE BRIDGE

Raitis Lacis
Forest Sector Competence Centre
raitis.lacis@inzenierbuve.lv

Abstract. The study presents data collection and data analysis principles and techniques applied for structural monitoring of timber-concrete experimental vehicular bridge. The framework of data acquisition for structural health evaluation is divided in two principal stages, namely, pre-monitoring stage and monitoring stage. Rational decision making and optimization of monitoring technical resources are demonstrated by establishing relationships between the measured variables in a context of the characteristics of the chosen measuring techniques. Field data are collected for two fundamental performance parameters of the structure, i.e. bending strains/stresses and deflection at a critical section of the bridge caused by heavy-duty vehicles. High degree of correlation is found between the two variables (r = 0.98) upon which any consequent monitoring activities can be based only on one measurement method found most suitable for long term technical conditions. As a result statistics of the other structural parameter can be derived by the established regression function. Furthermore, differences and causes of data dispersion obtained within the pre-monitoring stage are briefly discussed as well as some basic recommendations regarding the improvement of data reliability of both measuring techniques.

Keywords: bridge, monitoring, composite, timber-concrete, strain gauge, deflection.

Introduction

Structural health monitoring generally is associated with visual inspections in the predetermined time intervals, which also can be part of a larger bridge management system [1]. In digital era technical capabilities of monitoring have been significantly expanded along with the development of computer aided measurement systems and data storing capacities. Nowadays, bridge structures are commonly monitored using strain gauge systems, accelerometers, fiber optic sensors, digital transducers, etc. either in the wireless remote networks or as stand-alone systems, see [2; 3]. Typically monitoring is applied to the infrastructure elements, which require some approval of the expected structural response, for instance, when comparing real behavior of the structure to the assumptions and the outcome of a design phase. These usually are novel or complex structures, which have not been practiced before as well as older structures with significant damage accumulation prior to the decision of their decommissioning. Monitoring effectively provides engineering information regarding the safety of the structure at a particular moment of time and allows timely to track down changes of the structural response.

Although the timber-concrete composite (TCC) concept in its basic form is known since 1930ies [4], only with a recent development of glulam technology it has almost been rediscovered again [5]. Vehicular bridges are very demanding in terms of load capacity and therefore all assumptions made during the design stage have to be verified by field tests or by monitoring. In Latvia only two vehicular TCC bridges have been built so far. One is over the river Vaive (57º19’51”N, 25º23’31”E); year of construction 1977 [6].The other bridge is built in 2015 and serves as a full scale research object for this study and for TCC bridges in general [7]. The aim of this research, therefore, is to demonstrate the monitoring principles and methods adapted for the investigation of key load response aspects of the previously mentioned experimental TCC bridge. Any monitoring system is associated with certain expenses. It has to be technically and economically feasible and at the same time it has to provide sufficient engineering data for a decision maker to be able to interpret safety and structural performance of the bridge. The load response data collected during the monitoring allow engineering judgment to be formulated regarding the modelling assumptions and validity, robustness of the bridge, change of the loading regimes, damage accumulation as well as formal limit states defined by the standards (see Eurocode 5: Design of timber structures – Part 2: Bridges, [8]).

Materials and methods

Monitoring program was conducted on the 6m span experimental timber-concrete bridge, which was installed in the sand quarry (56º22’59”N, 23º27’47”E) characterized by the intensive heavy-duty vehicular activity due to the sand extraction and production. Typical weight of such vehicles depending on the axle configuration is around 300-520 kN.

Measurement categories and arrangement of the bridge instrumentation are illustrated in Figure 1. Basic technical and operational characteristics of the systems chosen for the monitoring purposes are summarized in Table 1.

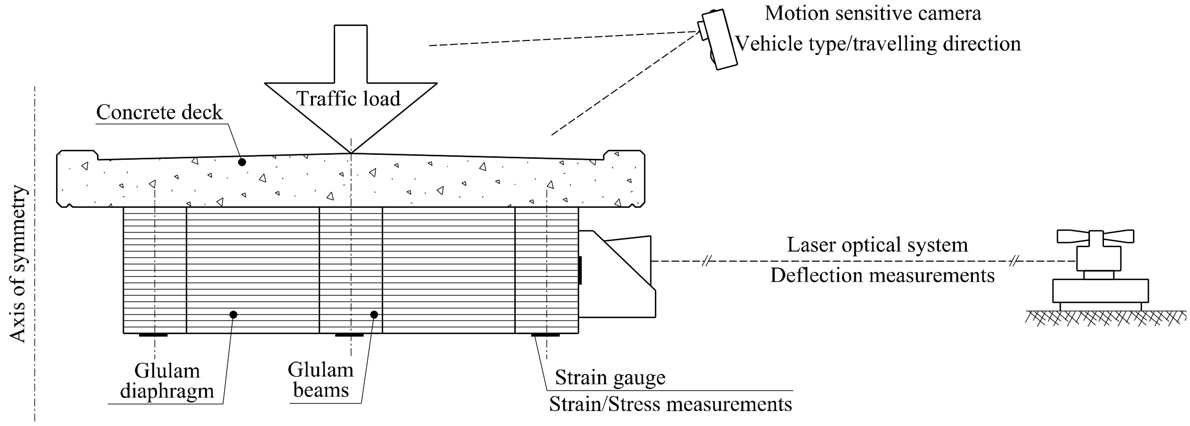

Fig. 1. **Layout of the measurement system**

Table 1

Characteristics of measurement systems

Variable and location	**Measurement technique**	**Characteristics of the measurement system**	
		Advantages	Drawbacks
Deflection of the bridge *Location: middle of the timber beam in longitudinal direction*	Laser optical system PSM 200 [9]	High precision (nominal resolution 0,01 mm)	Only one measurement point
		Dynamic measurements with flexible frequency setting (up to 500 Hz)	Suitable for short period measurements only
		-	Relatively expensive
		-	Assistance and presence of engineer required (computer driven system)
		-	Inflexible in terms of setting the optical path and positioning
Stress of glulam beam *Location: timber beam outer fibers at maximum negative bending moment*	Strain gauge network system: 50mm unidirectional gauges HBM, 2015) + HBM Spider8, [10]	Multiple measurement points	Relatively expensive
		Compact size (less attractive to vandalism)	Complex engineering knowledge involving (electric circuitry, temperature compensation algorithms, etc.)
		Dynamic measurements with flexible frequency setting (up to 50 Hz)	Value of material elasticity modulus required (for this study glulam GL24h is used, i.e. $E_{0,g,\ mean}$=11,6 kN·mm^{-2}
		Can be energy autonomous (long term suitability)	-
		Triggering of recording possible by predefined threshold value	-
Vehicle type and travel direction	Motion sensitive photo camera	Simple in installation and maintenance; autonomous	Vandalism sensitive
		Can be equipped with wi-fi for remote access	-

The plan of the monitoring program was conducted following the principal scheme depicted in Figure 2. Accordingly the whole program can be divided in two basic stages, i.e. the pre-monitoring stage and the monitoring stage. The pre-monitoring stage is necessary for establishment of statistical relationship between the variables in focus; structural response data in here are collected for one or two days only. In the monitoring stage itself measurements of only one variable are collected; the other variable is derived from quantitative relationships established in the pre-monitoring stage. Depending on the objectives of the monitoring it can be further prolonged for number of years or in some cases even decades just with one measurement system.

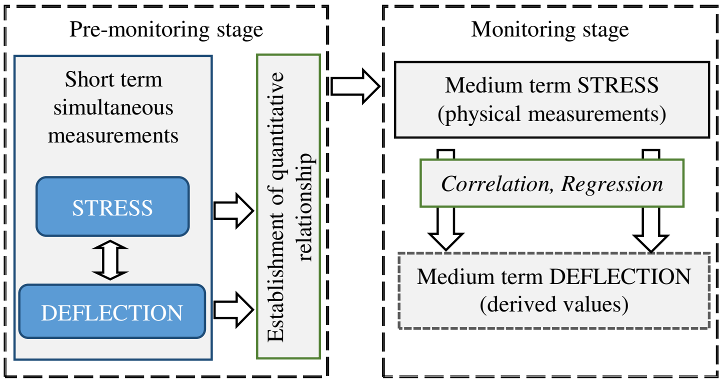

Fig. 2. **Principal scheme of monitoring**

Fundamental parameters characterizing structural response of the experimental bridge are bending stresses and deflection of timber-concrete beams. If relationship between these two variables is found to be representative, then monitoring with only one measurement system can be objectively and economically justified, thus providing considerable savings in the monitoring budget.

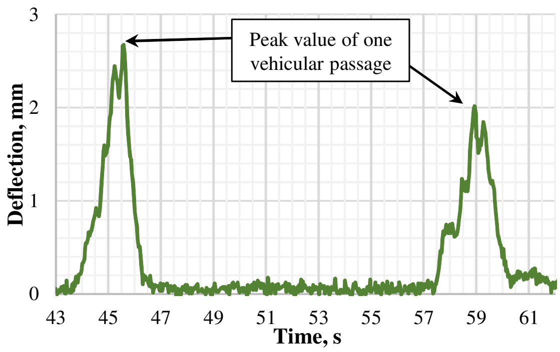

Fig. 3. **Deflection recording in time domain (fragment depicted)**

Typical statistical data of load effects have been built from the peak values of stress and deflection simultaneous measurements, see Figure 3. Total number of variable pairs analyzed in the pre-monitoring stage of this study is $n = 112$ and subsequent variable relationship forms the quantitative basis of the medium (long) term monitoring.

Results and discussion

Quantitative representation of the extracted peak values is depicted in Figure 4. High correlation is established between the variables (r = 0.98), suggesting that linear regression is applicable in this case (R^2 = 0.961).

Although traffic content during the pre-monitoring stage was similar on the vehicle-to-vehicle basis, the load effect data seem to concentrate in two clusters. The primary cause of the clustering has been recognized due to the different road conditions and surface smoothness at each end of the bridge. This assumption was studied in detail by decomposing the measurements regarding the respective vehicle travelling direction over the bridge, which were documented by the motion sensitive camera (data histograms in Figure 5 and Figure 6). Higher values of load effect can be expected wherever there is a source for dynamic excitation of the vehicle (bumps on the road in this case). This aspect has been researched for other general bridge-vehicle dynamic interaction cases, see [11; 12].

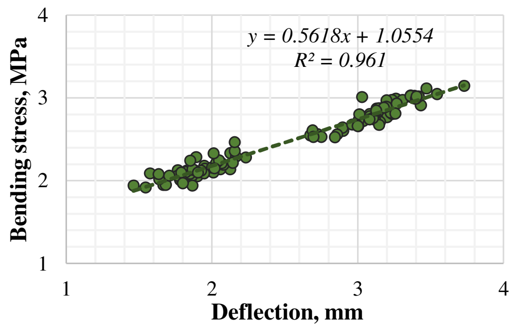

Fig. 4. **Bending stress and deflection data pairs.**

Decomposition of records allows evaluating spread of data for each variable. Given the different physical essence of the measured variables a non-dimensional data of spread estimator is used for the comparison of both. The coefficient of variation (COV), which is normalized measure of dispersion, is calculated as a ratio of sample standard deviation to sample mean and expressed in percentage. Bending stress measurements generally had lower relative spread – for decomposed data of travel directions around 5.3 % and 5.9 %. Respective numbers for deflection measurements are 8.9 % and 7.1 %. The differences suggest that the bending stress (strain measurements) in this experimental setup is a more reliable indicator compared to the deflection measurements. Most likely explanation of additional noise in the deflection data is the fact that the laser beam cannot be 100 % isolated from ground micro vibrations caused by the traffic on the bridge and embankments. Certain noise reduction, however, can be achieved if a sturdy and inert base is prepared for the laser beam unit of the deflectometer (concrete pad, for instance). Improved deflection data would also lead to a more precise regression model between the bending stress and deflection variables, which ultimately would improve the data quality of the monitoring stage as well.

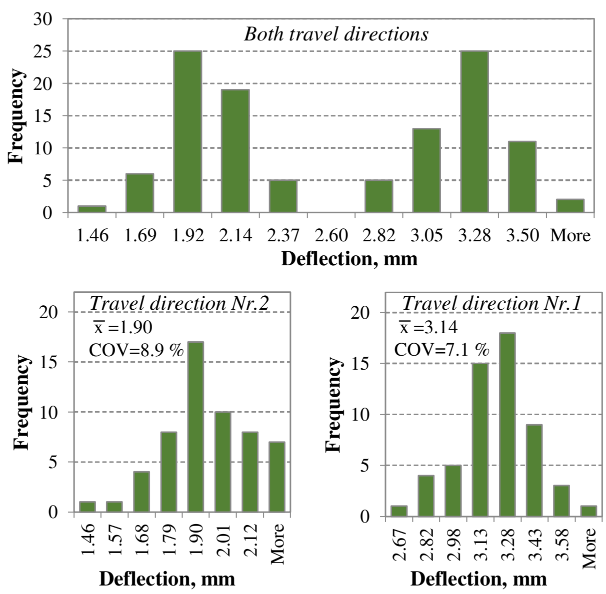

Fig. 5. **Deflection measurements (decomposed by directions)**

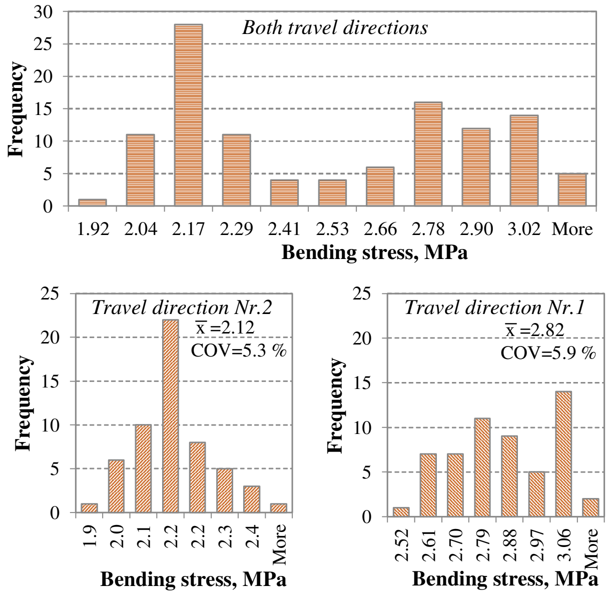

Fig. 6. **Bending stresses (converted from strain measurements and decomposed by directions)**

Even if the loading effects are considerably varying due to a number of factors described above, the functionality of statistical relationship still holds and provides essential information in health control of a structure. Based on the regression model assumed any further data collection can be conducted with only the bending stress measurement system, which according to Table 1 is more suitable for the medium and long term monitoring purposes. The deflection values necessary for serviceability control of the bridge can be derived mathematically using the relationship established from the pre-monitoring stage.

When using the strain gauge system some degree of uncertainty regarding timber strain conversion to bending stress values has to be acknowledged. In linear elastic range stress is directly proportional to the elasticity modulus (E) of the material. In this bridge project glulam of GL24h class is used with respective mean elasticity of such timber parallel to the grain $E_{0,g,\ mean}$=11.6 kN·mm^{-2} (according to EN 14080:2013, [13]). If monitoring is aimed for higher precision then standardized mean values may not give the best representation of the structural system. In such situations it is advised to test particular material for its exact elasticity. For timber-concrete bridges it can be done by non-destructible methods at the glulam beam prefabrication stage, see [14; 15].

Conclusions

1. Rationally planned monitoring activities can provide essential information regarding the load-bridge interaction in the post-construction phase.
2. Positive linear relationship is found between two fundamental load effects (stress and deflection) in the given load regime of the experimental TCC bridge, r = 0.98.
3. Magnitude of bending stress and deflection of the structural elements are dependent on the road conditions of the bridge. Bi-modal character of the response data is one of the possible indications of differing technical conditions or damage accumulation within the structural system or the road surface.
4. Deflection measurements with laser optics can be noisier if the laser beam unit is not properly isolated from external vibrations caused by the traffic.

Acknowledgements

This study is a part of the research project “Modern and Sustainable Wood Construction Research” administered by the “Investment and Development Agency of Latvia” in cooperation with “Forest Sector Competence Centre” Ltd., “Forest and Wood Products Research and Development Institute” Ltd. and “Inzenierbuve” Ltd. The project is co-financed by the European Regional Development Fund (agreement No. L-KC-11-0004).

References

1. Gattulli V., Chiaramonte L. Condition Assessment by Visual Inspection for a Bridge Management System. Computer-Aided Civil and Infrastructure Engineering, 20(2), 2005, pp.95-107.
2. Chaea M.J., Yoob H.S., Kima J.Y., Choa, M.Y. Development of a wireless sensor network system for suspension bridge health monitoring. Automation in Construction, Volume 21, 2012, pp.237–252.
3. Koh H.M., Choo J.F., Kim S.K., Kim C.Y. Recent application and development of structural health monitoring systems and intelligent structure in Korea. Structural health monitoring and intelligent infrastructure, 2003, pp. 99-112.
4. Rodrigues J., Dias A., Providencia P. Timber-Concrete Composite Bridges: State-of-the-Art Review. Bioresources. 8(4), 2013, pp. 6630-6649.
5. Simon A. Brücken in Holz-Beton-Verbundbauweise – Renaissance einer genialen Idee. VSVI Mecklenburg Vorpommern Seminar Brückenbau. Fachhochschule Erfurt, 2012.
6. Meža un koksnes produktu pētniecības un attīstības institūts. Koka tiltu projektēšanas vadlīnijas, Versija 3.0, 2015, pp.1-128 (in Latvian).
7. Lacis R. Circular hollow section connectors in timber-concrete composite structural elements. The Baltic Journal of Road and Bridge Engineering, 2016. Article in press, accepted in 10.11.2015.
8. Eurocode 5: Design of timber structures - Part 2: Bridges. European Committee for Standardisation. 2004.
9. Noptel, PSM-200 Displacement sensor. 2015. Available at: http://www.noptel.fi/download/nms/brochures/PSM2_213.pdf
10. HBM, Strain gauges catalog. 2015, Available at: http://www.hbm.com/fileadmin/mediapool/hbmdoc/technical/s1265.pdf
11. Feltrin G., Steiger R., Gsell D., Gülzow A., Wilson W. Serviceability assessment of a wooden trough bridge by static and dynamic tests. 11th World Conference on Timber Engineering WCTE, 2010, pp.1100-1108.

12. Park Y.S., Shin D.K., Chung T.J. Influence of road surface roughness on dynamic impact factor of bridge by full-scale dynamic testing. Canadian Journal of Civil Engineering, 32(5), 2005, pp. 825-829.
13. EN 14080:2013 Timber structures. Glued laminated timber and glued solid timber. Requirements. European Committee for Standardisation. 2014.
14. Sousa H.S., Branco, J. M., Lourenco, P. B. Prediction of global bending stiffness of timber beams by local sampling data and visual inspection. European Journal of Wood and Wood Products, 72(4), 2014, pp. 453-461.
15. Boström L. Determination of the modulus of elasticity in bending of structural timber – comparison of two methods. Holz als Roh- und Werkstoff, 57(2), 1999. pp.145-149.