Repeatability and precision of different static deflection measurements on a real bridge-part under outdoor conditions in view of damage detection

Tanja Kebig[1], Viet-Ha Nguyen[1], Michél Bender[2], Markus Schäfer[1], Stefan Maas[1]
[1]Department of Engineering, Faculty of Science, Technology and Medicine, University of Luxembourg, 6, rue Richard Coudenhove-Kalergi, 1359 Luxembourg, Luxembourg
[2]Department of Civil Engineering, Trier University of Applied Sciences, Schneidershof, 54293 Trier, Germany
email: tanja.kebig@uni.lu, vietha.nguyen@uni.lu, m.bender@hochschule-trier.de, markus.schaefer@uni.lu, stefan.maas@uni.lu

ABSTRACT: A large number of concrete bridges show increasing damage due to corrosion and fatigue. The traditional visual inspection and subsequent assessment of concrete bridges is carried out regularly by an experienced engineer. This type of inspection can be time-consuming, costly and leading to errors. Hence, there is a great interest in complementary, alternative and easy-to-implement methods for condition monitoring of bridges. The University of Luxembourg tested different approaches on a part of a real bridge. Various tests were performed in the healthy reference state, e.g. loading tests with a movable test load according to today's standards. The measurements in the reference state were repeated several times under outdoor conditions to monitor and document the real temperature influence. Displacement transducers were set up in the vertical and horizontal directions. Simultaneously, a new approach was used for determining the deflection with a laser-based system, that measured the displacements in the bridge's longitudinal direction by an oblique reflector panel under a well-defined angle. The data gained from the laser-based measurement system were compared to the data from classical displacement transducers. In general, the comparison of the two measuring systems shows quite similar results.

KEY WORDS: bridge inspection; reference state; laser-based measuring system; displacement transducer-based measuring system.

1 INTRODUCTION

Today, an increasing number of bridges are reaching the end of their lifetime. This is not solely a country-specific, but a worldwide problem. All over Europe, most bridges were built after the Second World War [1], [2]. In the past, the goal was to build new bridges and today it is to maintain them as long as possible and extend their lifetime. To be able to assess the condition of a bridge, it is important to uphold regular inspections. Visual inspections are widespread and performed at regular intervals by experienced engineers. The test intervals are regulated differently depending on the country (e.g. in Germany main inspection's interval is every 6 years [3]). This type of inspection is usually time-consuming and costly as bridges are often difficult to access and large areas have to be inspected. Furthermore, results depend on the experience of the engineer. Additionally, visual inspections (e.g. searching for cracks) do not always correctly assess a bridge's condition. Sometimes cracks can be hidden by coatings or in the special case of prestressed concrete bridges, the tendons are not accessible from the outside and cracks may not be visible even though the system is already internally damaged.

In the recent years, a lot of research has been done in the field of bridge monitoring and damage detection. The goal of monitoring systems is to permanently record the bridge's behavior and not to obtain snapshots like in visual inspection. Ideally, a permanent monitoring system should be coupled with an alarm system so that changes can be intervened promptly. If possible, a bridge should be monitored from the beginning of its life to detect changes as early as possible. However, the current discussion does not focus on new bridges but on the bridges that reach their end of lifetime. The question arises how these bridges can be monitored in addition to the visual inspection. A supplementary measuring system can assure diagnosis and thus allows extending the life of a bridge. There are different approaches concerning new inspection methods and tools [4, 5]. Therefore, it is necessary to know the healthy reference condition as well as to compare repeating subsequent measurements to it. In civil engineering, static load tests have a long tradition. However, they have the disadvantage that the bridge has to be loaded until a steady-state is reached. For the test period, the bridge has to be closed to traffic. In recent years, research has been increasingly focused on damage detection by dynamic measurements. For these, the bridge can be excited by an impact hammer, shaker, wind or traffic, knowing that the last two being more difficult to analyze as the excitation forces are not measured. Regardless of measurement type, the results can be compared with a Finite Element (FE) model. With Model Updating techniques, the FE-model is adapted to the measured data. The later damage analysis, is necessary to have a validated FE-model of the reference state. Such a model updating procedure is for instance detailed by Schommer [6].

The University of Luxembourg has been doing research in the field of damage detection of bridges for years. In the present study with a part of a real bridge, various tests were carried out in the healthy reference state, including static loading and quasi-static with a slow-moving load. The reference measurements were repeated several times to thoroughly check the bridge's behavior, especially under different outdoor conditions and for different bearing types.

This paper focuses on the comparison of two measurement systems during static and moving load tests. A conventional measurement system with displacement transducers is compared to a new approach based on a laser-based system provided by Lucks Technologies [7]. The system enables monitoring the bridge remotely almost in real-time. The test-setup and its instrumentation are presented in the following.

2 TEST-SETUP

The tested beam was part of a real bridge in Mersch / Luxembourg. It was built in 1957 and demolished in 2016 due to safety concerns and replaced by a steel bridge. The initial bridge was 256 m long and consisted of nine fields with spans between 25.8 m and 47.5 m. During the old bridge's demolition, one of the prestressed T-beams was transported to University of Luxembourg Campus Belval in Esch-sur-Alzette. It had a length of 25.7 m, a width of 1.9 m and a height of around 1.4 m. Due to the new casted foundations and bearings, bridge plate's upper edge was approximately 2.1 m above ground. Figure 1 displays the whole test setup with the moving load.

A fixed and a movable bearing supported the test beam. In a previous research project's test setup, the movable bearing was designed by using grease between two steel plates [6]. During these tests, stick-slip effects occurred due to the friction between the steel plates. Here, the impact of the movable bearing type was tested with 3 different types of movable bearing: round bar, mageba Lasto® Flonpad and steel plates with grease. The different movable bearings were exchangeable at any time with little effort and so it was possible to assess the impact of the bearing type and its friction in different seasons. But here, the focus is on the comparison of different displacement measuring systems. Therefore, only the setup with the round bar, shown in Figure 2, is presented.

Figure 1: Prestressed concrete beam with moving load

Figure 2: Movable bearing with a round bar

2.1 *Displacement transducer-based measurement system*

The recordings of temperatures and displacements in the healthy reference state started in May 2019. Both were measured continuously with a sampling rate of once per minute. For the temperature measurements, six PT100 were used at different positions. The ambient air temperature, the asphalt temperature and the concrete temperature were recorded. All temperature sensors were mounted in a hole with a depth of 100 mm, except the ambient air temperature sensor that was installed freely 1 m above the top of the bridge deck.
During the different tests, vertical and horizontal displacements were measured with eight inductive standard displacement transducers (type WA20, HBM). Those have a measuring range of 20 mm and a characteristic tolerance of ±1 %. Seven transducers measured the beam's vertical deflections (SVi) and one the horizontal displacement of the beam at the movable bearing (SH8). The positions of the transducers are detailed in Figure 3. The distance between the displacement transducers (SV1-SV6) was set to 5.4 m. SV3 and SV4 were located in the middle of the beam to check the inclination during the tests. SV7 was an additional measurement point (2.3 m outside the center). Figure 4 shows the bridge in the reference state, which corresponds to the unloaded and undamaged state and is defined with the load above the fixed bearing.

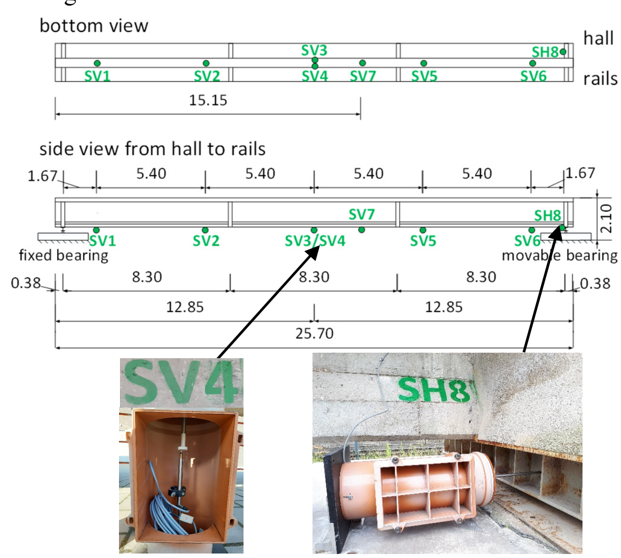

Figure 3: Displacement transducers SV1-SV7 and SH8 (above), SV4 (bottom left), SH8 (bottom right)

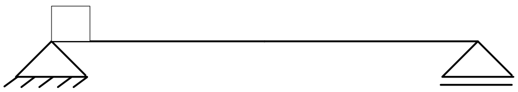

Figure 4: Reference state of the bridge

2.2 *Laser-based measurement system*

In January 2020, an additional measurement system was installed on the beam, i.e. the laser-based measurement system supplied by Lucks Technologies [7]. The general setup is shown in Figure 5. This system aims to record the movements of the bridge via horizontal distance measurements. For this test setup, it consisted of two laser sensors (L1 and L2), two reflector panels (RPs), a central processing unit (CPU) and two temperature sensors. The two lasers (class 2) were mounted on the concrete foundation on the fixed bearing side (Figure 6). These laser locations were defined as fixed points.

Figure 5: Laser-based measurement system of Lucks Technologies [7]

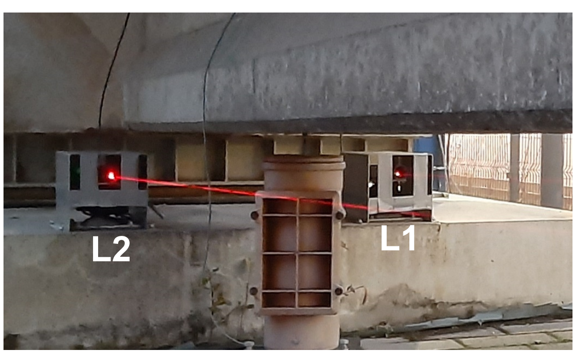

Figure 6: Position of two lasers on the concrete foundation at fixed bearing

The reflector panels were installed on the beam, forming the movable part of the measuring system (target). The targets were mounted at different angles with respect to the laser beam (Figure 7). Whenever the bridge was moving up or down, the measuring distance changed due to the inclination of the RPs. The lasers can detect a measuring distance between 1 and 100 m with a maximum sampling rate of 50 Hz [7]. For the test beam, the measured distances were between 11 and 14 m and the sample rate was set to 10 Hz.

The reflector panel of laser 1 (RP1) was installed at an angle of 60° between the panel and the incident laser beam (Figure 7 a) and b)). Due to the inclined reflector panel, it was possible to measure the vertical deflection indirectly. The measured distance thus included a horizontal and vertical displacement component. Separation into the individual components was only possible by measuring a second purely horizontal measurement distance with L2, as shown in Figure 7c) and d). The calculated deflection of L1 is compared to the displacement transducer data of SV4.

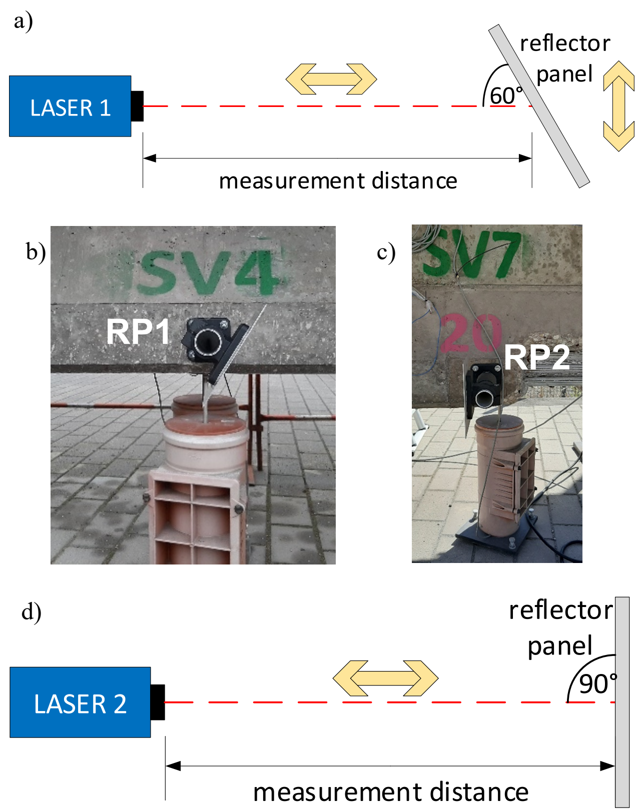

Figure 7: a), b) Laser 1 with reflector panel of 60°, c), d) Laser 2 with reflector panel of 90°

2.3 *Tests*

A load of approximately 8.8 t was used for the static loading tests. The load consisted of a trolley with nine steel beam blanks (see Figure 1). Figure 8 shows the two states of static tests:

- Unloaded state → Trolley over fixed bearing
- Loaded state → Trolley in the middle of the beam

These tests were carried out multiple times, so that measurement data were available at different temperatures. The beam remained in a loaded or unloaded state for several days. For comparing the two measurement systems, only the displacement transducers SV3, SV4 and SH8 were important.

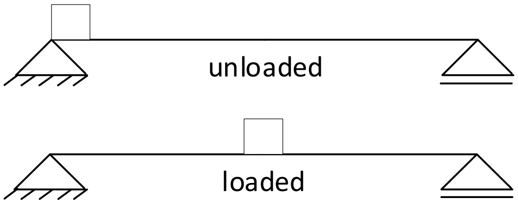

Figure 8: Static test – unloaded and loaded state

In addition to the static loading tests, moving load tests were performed. During the moving load test, the trolley moved slowly over the bridge at a speed of about 1 m/min, meaning that one crossing took about 20 minutes. Figure 9 shows an exemplary measurement procedure:

- Trolley moves from fixed bearing to movable bearing
- Trolley stops over movable bearing
- Trolley moves from movable bearing to fixed bearing

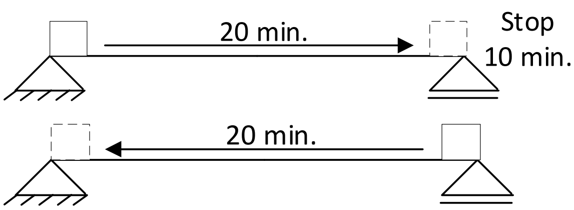

Figure 9: Moving load test with trolley

2.4 *Analysis of measurements*

The calculations below compare a contact-based traditional precise displacement transducer system with a new contactless laser-based measurement system. The classical inductive transducers provide only values in one direction, why it was easy to read directly the bridge's deflection at the different measuring points. The measurement system was initialized at the beginning of each evaluation period and all sensors were set to zero.

Due to the inclined panel, the distance measurement of L1 contained a displacement component in both horizontal and vertical directions, as seen in Figure 11. In the first step, these measurement raw data had to be split into the two components. L_0 was defined as the initial length and set the zero position of the measurements (Figure 10).

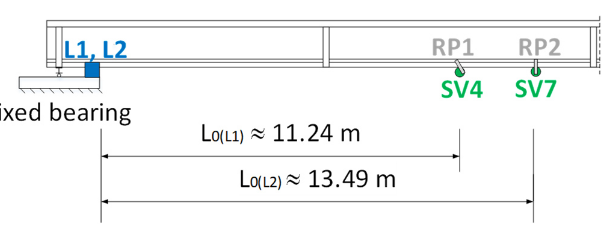

Figure 10: Location of lasers, reflector panels and corresponding displacement transducers

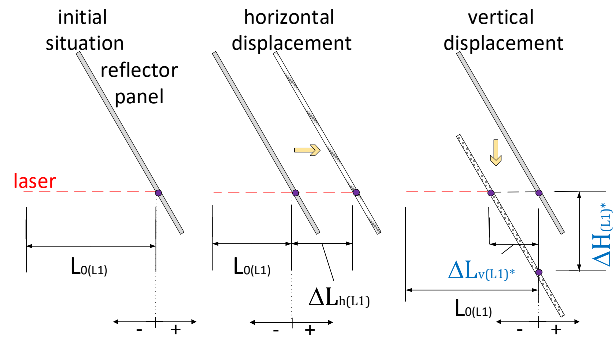

Figure 11: Inclined reflector panel 1 – horizontal and vertical displacement component

To separate the vertical component ($\Delta L_{v(L1)^*}$) from the distance measurement of L1 ($\Delta L_{h+v(L1)}$), a second purely horizontal distance measurement was necessary. Therefore, L2 measured the horizontal movement with a vertically aligned reflector panel (Figure 12). Figure 10 shows that the two reflector panels were not installed at the same x-position. Hence, the pure horizontal measurement of L2 ($\Delta L_{h(L2)}$) was converted or corrected to the position of L1 ($\Delta L_{h(L1)^*}$). Then it was possible to separate the vertical component from the horizontal component and calculate the pure vertical deflection $\Delta H_{(L1)^*}$. Equations 1-5 show the calculation steps. The displacement in the vertical direction was defined positively downwards. Therefore, a minus was placed before $\Delta L_{v(L1)^*}$ in Eq. (5). The '*' in the equations indicates calculated values.

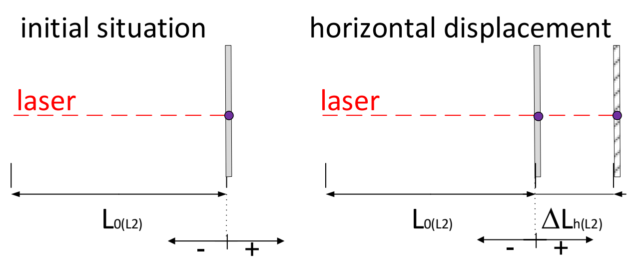

Figure 12: Vertical reflector panel 2 – initial situation (left), horizontal displacement (right)

$$\Delta L_{h(L1)^*} = \Delta L_{h(L2)} \cdot \frac{L_{0(L1)}}{L_{0(L2)}} \tag{1}$$

$$\Delta L_{h(L1)} = \Delta L_{h(L1)^*} \tag{2}$$

$$\Delta L_{h+v(L1)} = \Delta L_{h(L1)^*} + \Delta L_{v(L1)^*} \tag{3}$$

$$\Delta L_{v(L1)^*} = \Delta L_{h+v(L1)} - \Delta L_{h(L1)^*} \tag{4}$$

$$\Delta H_{(L1)^*} = -\Delta L_{v(L1)^*} \cdot \tan(60°) \tag{5}$$

3 RESULTS

The first step was to refer the measured data to an initial start value. Therefore, only deviations from the start value (Δ-values) are considered in the following figures. Figure 13 shows the measured horizontal displacement of both lasers during two weeks in October 2020. The yellow raw data line shows the change of the measured distance of L1, containing both horizontal and vertical components. The red line shows the deviations of the measured distance of L2, which contains only the bridge's pure horizontal displacement. From 13/10/2020 to 23/10/2020, the bridge was in the loaded state. On 23/10/2020, the trolley was moved from the middle of the beam to the fixed bearing. Then, two moving load tests were performed. Afterward, the bridge was left in the unloaded state. The change from the loaded to unloaded state is clearly visible in Figure 13 by the big step on 23/10/2020. The remaining smaller fluctuations result from the temperature change during day and night.

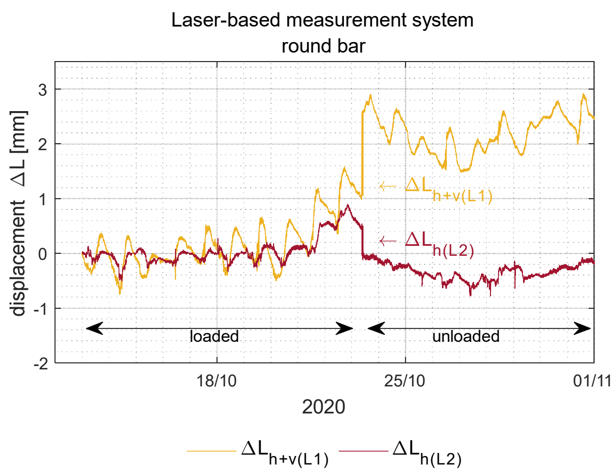

Figure 13: Laser-based measurement system – displacement ΔL, round bar, 13/10-31/10/2020, sample rate 1/min

To compare the laser data, the measured values of L2 were converted to the measuring point of L1 with Eq. (1). Equation (1) is based on the assumption that the bridge moved linearly in the longitudinal horizontal direction starting from 0 at the fixed bearing to a maximum at the movable bearing. The result of this calculation is shown in Figure 14 by the green line $\Delta L_{h(L1)*}$. The blue line shows the vertical displacement component $\Delta L_{v(L1)*}$ calculated with Eq. (4).

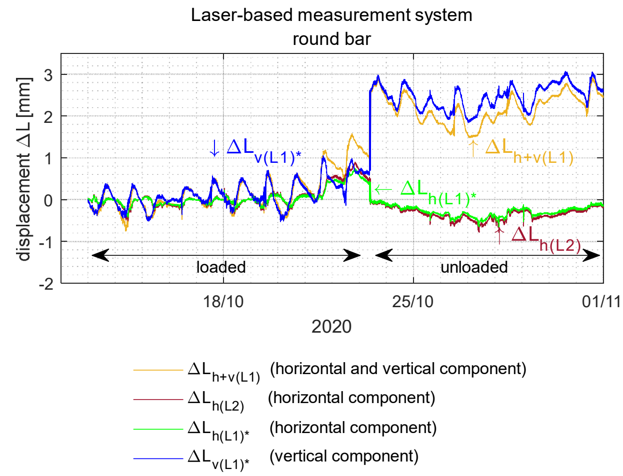

Figure 14: Different displacement components in the middle of the beam, 13/10-31/10/2020

Figure 15 is split into three parts. The upper part shows the horizontal displacement u or ΔL_h in the middle of the beam. The laser measurement $\Delta L_{h(L1)*}$ (green) is compared to the calculated horizontal displacement at position SV4 (orange). $\Delta L_{h(SV4)*}$ is half of the horizontal displacement of SH8 ($\Delta L_{h(SH8)}$ is not represented in the figure). The middle graph displays the deflection w or ΔH in the middle of the beam. $\Delta H_{(L1)*}$ was calculated with Eq. (5), whereas for reasons of comparison, $\Delta H_{(SV4)}$ shows directly the measured data of the displacement transducer SV4. In the vertical direction, the measurement signals deviate between -2.80 mm to +0.95 mm within two weeks. The lower part displays the different temperatures: T3 (concrete temperature), T5 (asphalt temperature) and T6 (ambient air temperature). Both measurement systems were exposed to the same temperature fluctuations.

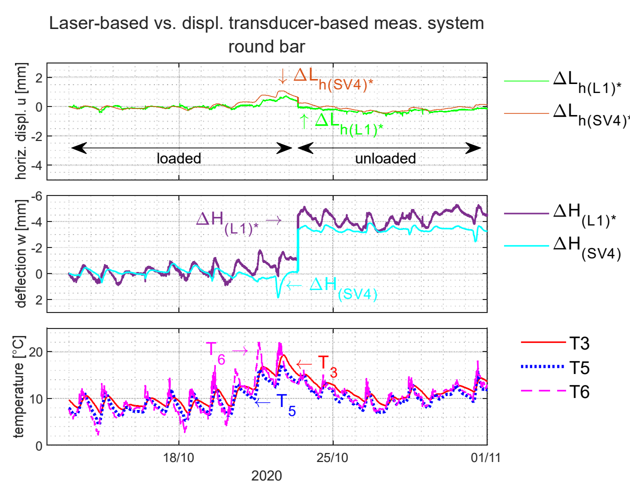

Figure 15: Laser vs. displacement transducer – deflection and displacement in the middle of the beam, 13/10-31/10/2020

Figure 16 shows a one-day measurement in detail. October 22, 2020, was a sunny day and the temperatures varied considerably. The measurements were set to zero at midnight. The deflection values of SV4 followed the concrete temperature T3, while L1 was closer to the air temperature (T6). The largest deviations occurred between 11:00 to 19:00, where a deviation up to -1.63 mm was observed. The smallest difference during this day was +0.55 mm.

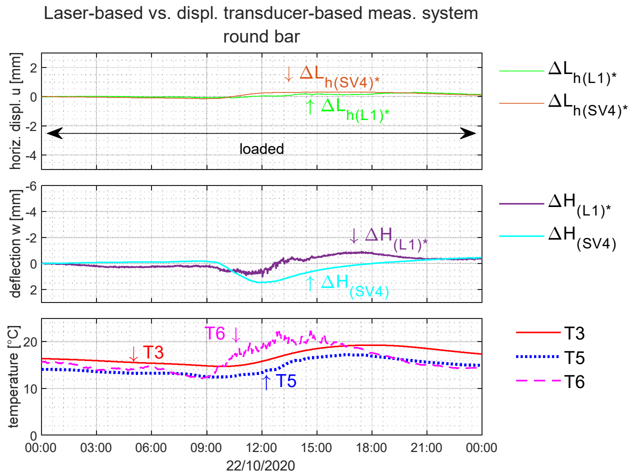

Figure 16: Laser vs. displacement transducer – deflection and displacement in the middle of the beam, 22/10/2020

The bridge's deformations during a moving load test are shown in Figure 17, where the different crossings are numbered in the middle chart. No.1 shows the first crossing of the bridge from fixed to movable bearing and no. 2 the crossing in the opposite direction. The temperatures during this test phase were quite constant. The deviation of the deflection w was from -0.35 to 0.09 mm. Two additional measurement points were selected and evaluated. In the first crossing, the trolley reached the center of the bridge at 09:31 AM and in the second crossing at 10:04 AM. The relative error for the horizontal displacement was -4.6 % [-12.0 %] and for the deflection -3.3 % [-2.8 %] at 09:31 AM [at 10:04 AM].

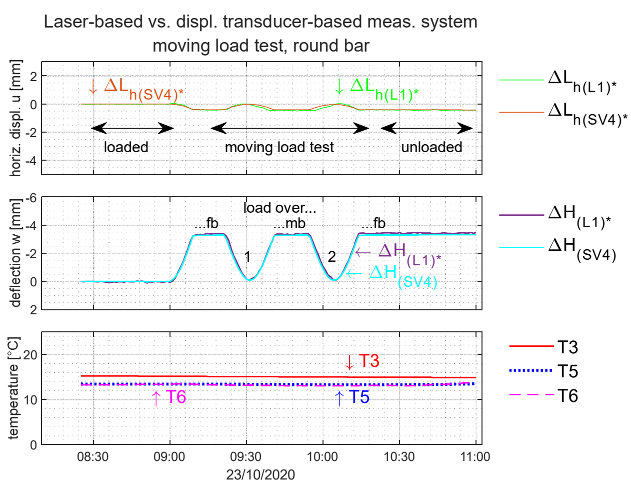

Figure 17: Laser vs. displacement transducer – deflection and displacement in the middle of the beam, moving load test, 23/10/2020

Table 1 summarizes the results of the measurement system comparison depending on the analyzed period. In the upper part, the horizontal displacement values are shown. Results of the deflection in the middle of the beam are presented below. The value max Δ shows the maximum deviation between both measurement systems of all delta values in the positive direction and min Δ the maximum deviation in the negative direction. The sum of both Δ-values results in the deviation range value. The RMSE (Root Mean Square Error) for the horizontal displacement is 0.18, 0.11 or 0.06 mm depending on the observed measurement period. For the vertical deflection, the RMSE is between 0.83 and 0.11 mm.

Table 1: Summary of measurement system comparison [mm]

horizontal displacement u	12/10/2020-31/10/2020	22/10/2020 sunny day	23/10/2020 moving load
max Δ [mm]	0.27	0.11	0.09
min Δ [mm]	-0.61	-0.26	-0.20
dev. range [mm]	0.89	0.37	0.29
mean [mm]	-0.12	-0.03	-0.02
RMSE [mm]	0.18	0.11	0.06

vertical deflection w	12/10/2020-31/10/2020	22/10/2020 sunny day	23/10/2020 moving load
max Δ [mm]	0.95	0.55	0.09
min Δ [mm]	-2.80	-1.63	-0.35
dev. range [mm]	3.76	2.18	0.44
mean [mm]	-0.53	-0.22	-0.07
RMSE [mm]	0.83	0.62	0.11

4 CONCLUSIONS

The laser-based measuring system achieves promising results for the vertical deflection w and for the horizontal displacement u. For the horizontal displacement, the deviation range was 0.89 mm within 2 weeks with an RMSE of 0.18 mm. On a sunny day, the deviation range was 0.37 mm with an RMSE of 0.11 mm. The deflection varied over a wider range. During the 2 weeks, the deviation range was 3.76 mm (RMSE 0.83 mm) and for one day, the deviation range went up to 2.18 mm (RMSE 0.62 mm). The shorter the measurement period, the smaller the temperature influences and consequently the smaller the deviations (see results of moving load test). The deviation range of measurements can be influenced by the following factors: angle of the reflector panel, alignment of the lasers, mounting device of the reflector panel. For future experiments it is suggested that the pure horizontal displacement is measured at the same point as the deflection. This could improve the measurement accuracy.

Special features of the laser-based measuring system are the wireless connection between the reflector panel (target) and the laser sensor. The lasers work with the constant speed of light. Since the measurement distance is permanently installed and contains no moving parts, there is no mechanical wear. If a laser sensor needs to be replaced, the old data can be read directly. The use of the contacting inductive displacement transducers is only possible in rare situations on existing bridges. On real sites, the free distance between ground and bridge is typically too high to allow their use.

To detect, localize and quantify damage at an early stage, it is important to know the behavior of the bridge in a healthy reference state. This includes repeated dynamic and static measurements and sagging, i.e. a long-term move down due to own weight. Here, the present paper's focus is on recording static displacement using two different measurement approaches. It is well known that temperature induced displacement effects on real bridges can be in the magnitude of the damage induced effects. Therefore, temperature effects must be compensated before the measured data are finally assessed, e.g. by combining them with the computational models. Based on the measurements, comparative calculations are carried out using the FE-method. A model updating process can for instance adjust the stiffness matrix to the measured data and thus lay bare the locations and degree of stiffness loss, i.e. the positions of damage

ACKNOWLEDGEMENTS

Supported by the Luxembourg National Research Fund (FNR) (11607841) [8]. The authors acknowledge the high value contribution of Administration des ponts et chaussées Luxembourg [9] and Lucks Technologies, Hamburg [7].

REFERENCES

[1] A. Žnidarič, V. Pakrashi, E. O'Brien and A. O'Connor, *A review of road structure data in six European countries*, proceedings of the Institution of Civil Engineers-Urban design and planning, 164(4), 225-232, 2011.

[2] Bundesanstalt für Straßenwesen, Brückenstatistik (Stand: 01.09.2020), available: https://www.bast.de/BASt_2017/DE/Statistik/Bruecken/Brueckenstatistik.pdf;jsessionid=C146A4C6F6B22EEF8135ABD9D940682B.live21302?__blob=publicationFile&v=15, [Accessed 31 December 2020].

[3] DIN 1076:1999-11, Ingenieurbauwerke im Zuge von Straßen und Wegen; Überwachung und Prüfung, Beuth Verlag, Berlin.

[4] M. P. Limongelli and A. Orcesi, *COST ACTION TU1406, Quality specifications for roadway bridges standardization at a European level, Report of the innovation subgroup*, 2019, available: https://www.tu1406.eu/wp-content/uploads/2019/10/tu1406-report-innovation-subgroup-v2.pdf, [Accessed 31 December 2020].

[5] M. Sperber, R. Gößmann, C. Reget, J. Müller, J. Nolden, R. Köhler and L. Kremkau, *Unterstützung der Bauwerksprüfung durch innovative digitale Bildauswertung-Pilotstudie*, Berichte der Bundesanstalt für Straßenwesen, Unterreihe Brücken- und Ingenieurbau 139, 2017.

[6] S. Schommer*, Damage detection in prestressed concrete bridges based on static load testing, sagging and modal parameters, using measurements and model updating,* Doctoral dissertation, University of Luxembourg, Luxembourg, 2017, available: https://orbilu.uni.lu/handle/10993/32971, [Accessed 31 December 2020].

[7] C. Lucks, *Bauwerksmonitoring mit laser-basierter Verformungsmessung… am Beispiel einer Spannbetonbrücke*, available: https://www.bauwerkmonitoring.de/app/download/7699105011/Bauwerkmonitoring+08.05.2020.pdf?t=1595930447, [Accessed 31 December 2020].

[8] Luxembourg National Research Fund (FNR), available https://www.fnr.lu/funding-instruments/afr/, [Accessed 31 December 2020].

[9] Administration des ponts et chaussées, available : https://pch.gouvernement.lu/fr.html, [Accessed 31 December 2020].