DOI: 10.3217/978-3-99161-057-1-085

Short- and long-term monitoring of bridges using terrestrial laser scanning data

Thomas Moser[1], Werner Lienhart[1, ORCID]

[1] Graz University of Technology, Institute of Engineering Geodesy and Measurements Systems, Steyrergasse 30, 8010 Graz, Austria

email: thomas.moser@tugraz.at, werner.lienhart@tugraz.at

ABSTRACT: Terrestrial laser scanning (TLS) is commonly used to capture 3D point cloud data of the environment. In this article we demonstrate that TLS data can also be used to measure long-term and daily deformations of bridges. On one hand full dome laser scanning is used to determine the deformations of entire bridge pillars whereas scanning total stations are well suited to capture segments and profiles of bridge pillars. We highlight that an accurate point cloud registration and appropriate processing algorithms are crucial to reliably determine deformations in the millimeter range. The capabilities of our approach are demonstrated on two large highway bridges where the bending of bridge beams due to temperature changes and one side sun illumination are investigated.

KEY WORDS: Terrestrial laser scanning, bridge monitoring, structural health monitoring

1 INTRODUCTION

Many large highway bridges in Europe were built in the 1960s and 70s. While the lifetime of these bridges was designed to be up to 100 years, reality shows that lots of bridges do not meet this expectation. One of the reasons is the increased load due to the rapid increase of traffic volume within the last decades (Figure 1 [1]).

As the replacement of the respective structures will take several years, aging objects need to be kept in service in the meantime. To ensure safe operation during this period, monitoring measures are often taken to obtain crucial data for decision making, e.g. prioritize structural measures, restrict traffic or similar.

One way to gather reliable data of bridges is to capture geometric changes of the structures. A geometric change can either be induced by loading of the bridge, by changing environmental conditions or by damages. Deformations can be measured with traditional geodetic sensors such as Robotic Total Stations (RTS), where one or multiple discrete points are measured and the absolute coordinates are determined in 3 dimensions with high accuracy. Another possibility is to capture multiple point clouds with Terrestrial Laser Scanners (TLS) over time. The different point clouds can be compared to each other and deformations can be computed throughout the entire object.

With these kind of remote sensors, not only static deformations can be captured but also dynamic changes during the pass of a load over a bridge. Modern RTS can track individual prisms with 20 Hz [2] and many TLS can also be operated in profile mode The Profile Laser Scanner (PLS), works just as an TLS, but the rotation of the standing axes is suppressed. Therefore, the profile is measured multiple times per second and the relative deformations can be captured dynamically in 2D [3]. When using an RTS dynamically, the instrument stays with observing just one prism at the time but can take angle and distance measurements with up to 20 Hz and therefore capture the dynamic 3D deformation of this prism. A study about the performance of both of the methods as well as Profile Laser Scanners can be found in [2] and [4]. Additionally, some modern RTS have also a scanning feature included. These so called Multi Stations (MS) have a slower scanning speed than conventional TLS and therefore are not well suited for full dome scanning but well applicable for scanning defined sections of a scene, e.g. a tunnel face or bridge pillars.

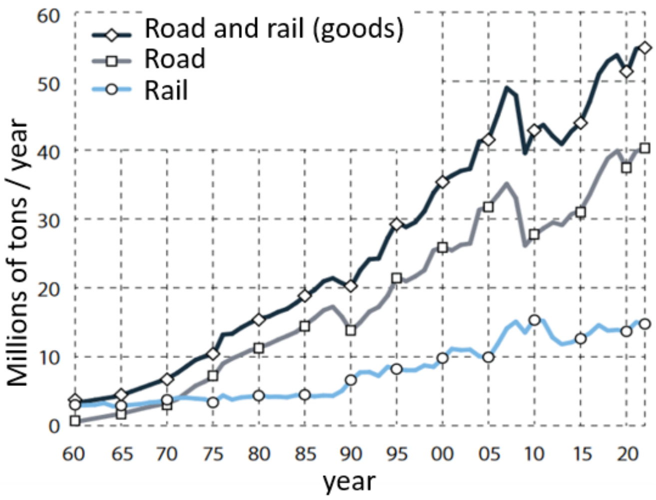

Figure 1. Exemplary trend of good transportation at the Brenner pass for Railway and road transportation from 1960 – 2022, translated to English after [1].

While dynamic measurements are mostly done to assess the deformations of structures due to dynamic loading, e.g. overpass of a truck or other dynamic excitation, static measurements are used to either determine the deformations

DOI: 10.3217/978-3-99161-057-1-085

during static load tests or to observe changes due to environmental effects such as temperature or structural changes. One important criterion for the comparison of multi-epoch data is the registration of point cloud data to obtain reliable results. This is challenging as bridges do not always offer stable areas to connect multiple scan epochs.

In this paper we demonstrate that it is possible to compare multiple scanning epochs that are taken over several days with a scanning total station, as well as point cloud data captured by a classical TLS with target-based registration over a longer period of time on a real-life bridge object. This work focuses on the deformation of the bridge pillars. The deformation of the bridge decks e.g. during load tests are discussed in [2], [4] and [5].

2 BRIDGE OBJECTS

2.1 Aurachbrücke

The Aurachbrücke, is the highest bridge of the A1 Westautobahn in Austria, located between Linz and Salzburg. The observed bridge is a temporary building for the time of the replacement of the old bridge. The bridge is a concrete box girder structure with 5 spans and a total length of 420 m.

2.2 Gschnitztalbrücke

Situated in Steinach am Brenner in Tyrol, the Gschnitzalbrücke (Figure 2) is part of the most frequented alp passage in Europe, the Brenner highway. The bridge consists of 7 spans with a total length of 560 m. The deck is curved with an arch radius of about 600 m. The steel-concrete composite bridge was built as a continuous beam in the 1960s for two lanes in each direction. In the 1980s an additional third lane was built in each direction due to upcoming traffic. One of the 7 spans is observed via TLS and RTS.

3 MEASUREMENT SETUP

3.1 Aurachbrücke

The measurements at the Aurachbrücke were taken within 48 hours from 06.09.2024 to 08.09.2024 with a Leica MS60 RTS with scanning function. Every 15 minutes the following sequence of measurements was performed: First multiple prisms were measured within 3 sets of combined angle and distance measurements. Afterwards, parts of the pillars 3 and 4 were scanned, see Figure 3. The scans included areas pointing along and across the bridge's direction. This setup creates the possibility to derive the 3D bending line of the pillars. In this paper, only pillar 3 is considered.

Additionally, IoT tilt sensors were mounted on top of every pillar for long term monitoring. The measurement rate of these sensors was also set to 15 minutes. Hence, three different data types (3D prism coordinates, point clouds, tilt readings) are available for comparison.

3.2 Gschnitztalbrücke

At the Gschnitztalbrücke in Tyrol, TLS and RTS measurements are taken epoch-wise 4 times a year. The measurements are taken at night from 10 p.m. onward to avoid truck traffic affecting the measurements. In Figure 2 the setup with the laser scanner in span 7 and the setup of the static total station is shown. A Leica RTC360 was used as TLS. This instrument performs full dome scans and hence the captured 3D point cloud includes the whole bottom side of the girders as well as the pillar and end abutment of the bridge. The measurement time is about two and a half minutes per scan for the highest scanning resolution (without pictures). The RTS takes measurements of the prisms sequentially. Not only the prisms on the bridge are measured, but also control points are included in the measurements.

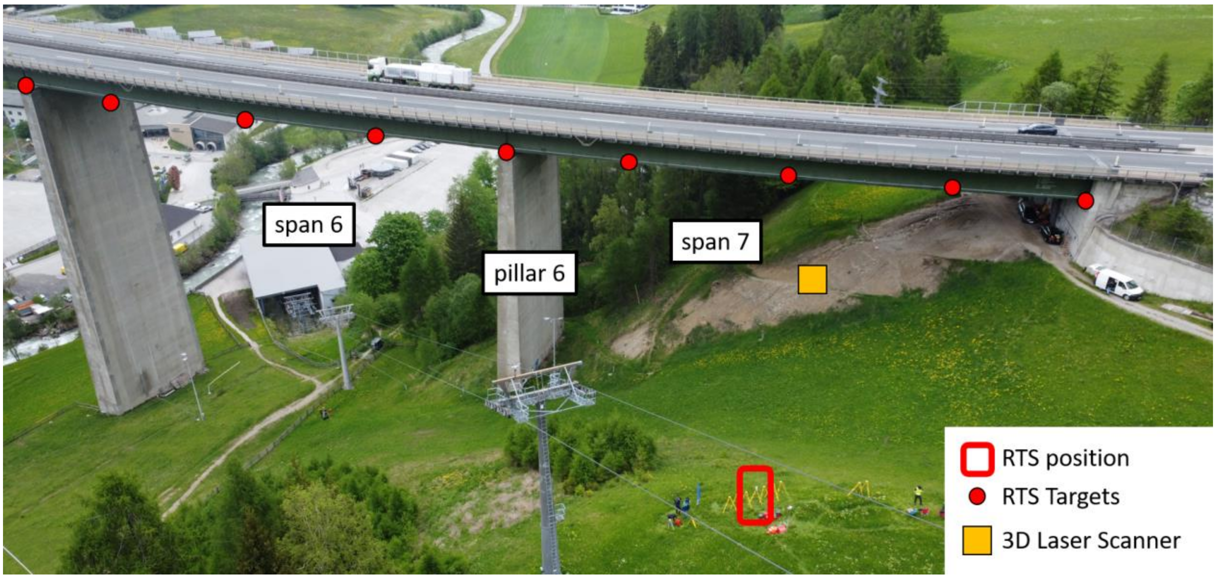

Figure 2. Overview at the Gschnitztalbrücke with span 6 & 7.
The measurement setup shows the prisms at the spans, as well as the RTS position and the TLS position.

DOI: 10.3217/978-3-99161-057-1-085

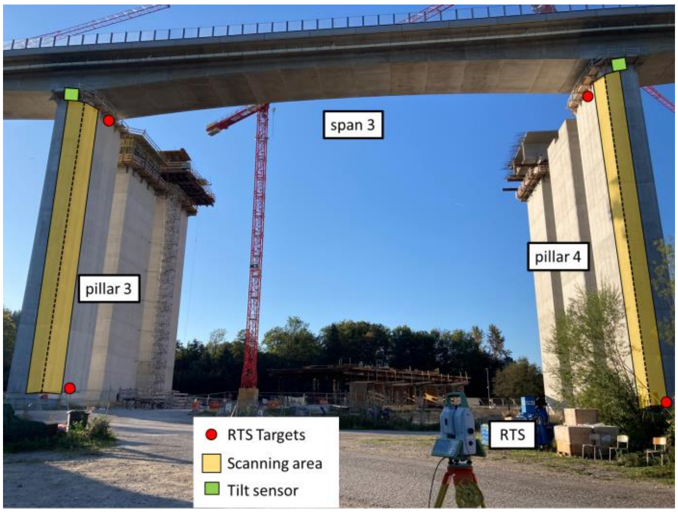

Figure 3. Setup of the RTS at Aurachbrücke.
The scanning areas can be seen in light yellow, as well as the measured prisms mounted at the pillars (red circles)

4 DATA ASSESSMENT

4.1 Aurachbrücke

The Leica MS60 is capable of not only measuring single points sequentially, but also capturing point clouds. Compared to a real TLS, the scanning speed is rather slow, but the advantage of the scanning total station is, that specific Regions of Interest (RoI) can be chosen which are scanned. This reduces the scanning time, and the definition of the scans can be used multiple times, so a time series of scans can be captured. All these measurements are triggered externally by a laptop using a python script and Leica GeoCom for communication.
Combining the scanning function with classical point-wise measurements, the following data is available for every epoch (15 minutes):

- 3 sets of all prism points
- 1 scan of each of the two pillars 3 & 4

The scan resolution is about 5 cm in horizontal and 5 cm in vertical direction. To compute the deformations of the pillar, horizontal bands of 0.5m are cut from the point cloud along the Z-component for the longitudinal and cross section of the pillar. The points within each band are then averaged for every 5 cm in height and a moving average filter is applied to the remaining vector with a size of 0.2 m. To eliminate stationing errors, the bottom part (1 m) of the pillar is supposed to be fixed, so the mean value of the lowest meter is subtracted from every epoch. As reference epoch serves the first captured epoch on 06.09.2024 at around 20:00.

For the sequentially measured object points a free stationing is computed for every epoch and the polar points are derived from there. The coordinates can be transformed into along and across direction of the bridge to compare the results of both methods. A bending line can also be calculated, assuming, that the bending originates from the temperature differences of both sides of the pillar which is calculated by

$$\Delta T = \frac{d \cdot 2 \cdot B}{\alpha_T \cdot H^2} \qquad (1)$$

whereas d is the displacement, B is described as the width of the pillar, α_T is the temperature expansion coefficient of the material and H the height of the pillar. The biggest temperature differences are calculated to be less than 3 K.
Also, for the tilt sensor data, a theoretical bending line is calculated to be compared to the captured point cloud and pointwise prism data.

4.2 Gschnitztalbrücke

The scans at the Gschnitzalbrücke were taken at night with the Leica RTC360 while no heavy traffic was passing the bridge. Hence the load free state of the bridge was captured and only environmental effects are affecting the structure. The registration of the point clouds was target based, whereby four targets were setup and their positions determined via RTS measurements. Different approaches to register deformed point clouds are available and investigated by many researchers, one of the latest examples is stated in [6].
In this case the comparison of the point clouds of the pillars was done using a Cloud to Cloud (C2C) comparison directed to the surface plane of the examined pillar. So, it is possible to show the deformation of the pillar over the entire surface. Comparisons with the RTS data are not shown in this work but can be seen in [5]. Other state of the art methods of comparing point clouds are described in [7].

5 RESULTS

5.1 Aurachbrücke

The results of the 48 hours measurement reveal interesting significant temperature dependent deformations. The behavior of the pillar can be followed for every 15 minutes over 2 full days.

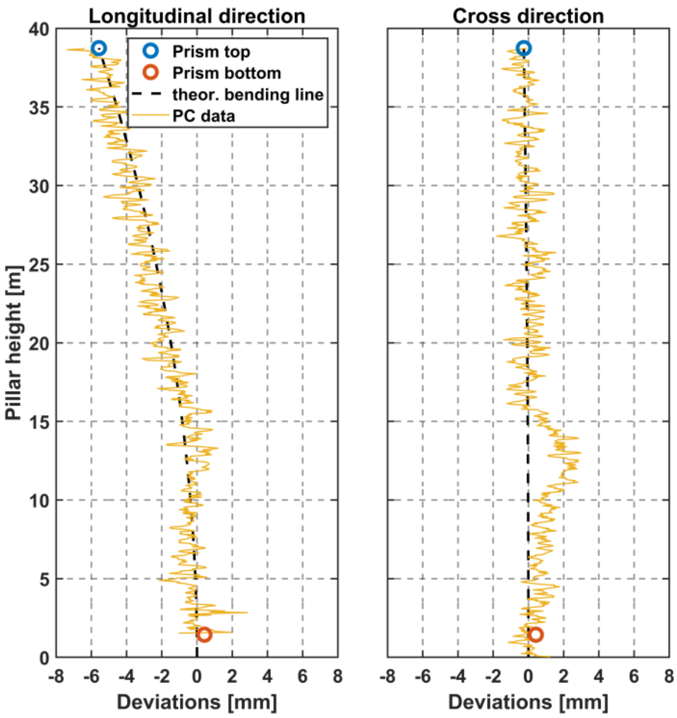

Figure 4. Deformation of Pillar 3 in longitudinal and cross direction for the epoch 07.09.2024 12:00 compared to the first captured epoch (06.09.2024 20:00)

DOI: 10.3217/978-3-99161-057-1-085

In Figure 4, one epoch captured at noon is shown relatively to the first epoch measured in the evening. In longitudinal direction, the bending of the pillar is clearly visible and matches well the calculated theoretical bending line that is derived by the prism on top of the pillar.

Looking at the cross direction, the prism on the top as well as the scanning data do not show significant deformations at the height of the pillar. However, a strong deformation is noticeable at the height of about 10 to 15 m. The source of this anomaly was not clearly found, but it seems unlikely that the pillar deforms that way. Yet, looking at the waterfall Figures 5 and 6, it can be seen, that the apparent deformation occurs in both directions at the same time of day in the same height of the pillar. This indicates, that the deformations may occur due to a combination of angle of incident of the sun and the angle of impact of the laser distance measurement by the RTS.

Also, it can be seen in Figure 5 that the bending in longitudinal direction rises beginning on top of the pillar and grows with time over the day and peaks at about midday. After the deformation is widely dismantled, a short deformation in the other direction can be seen on the second day at around 16:00. But this coincides also with the described anomaly and therefore is not considered real deformation but rather a problem with the laser distance measurement due to the surface of the pillar.

The peak of bending on midday is explainable by the East-West alignment of the bridge which implies that the pillars are illuminated from one side before and from the other side after midday.

To further validate the quality of the point cloud acquisition, a band of 1 m is cut from the top of the point cloud and averaged for every epoch. This timeseries can be directly

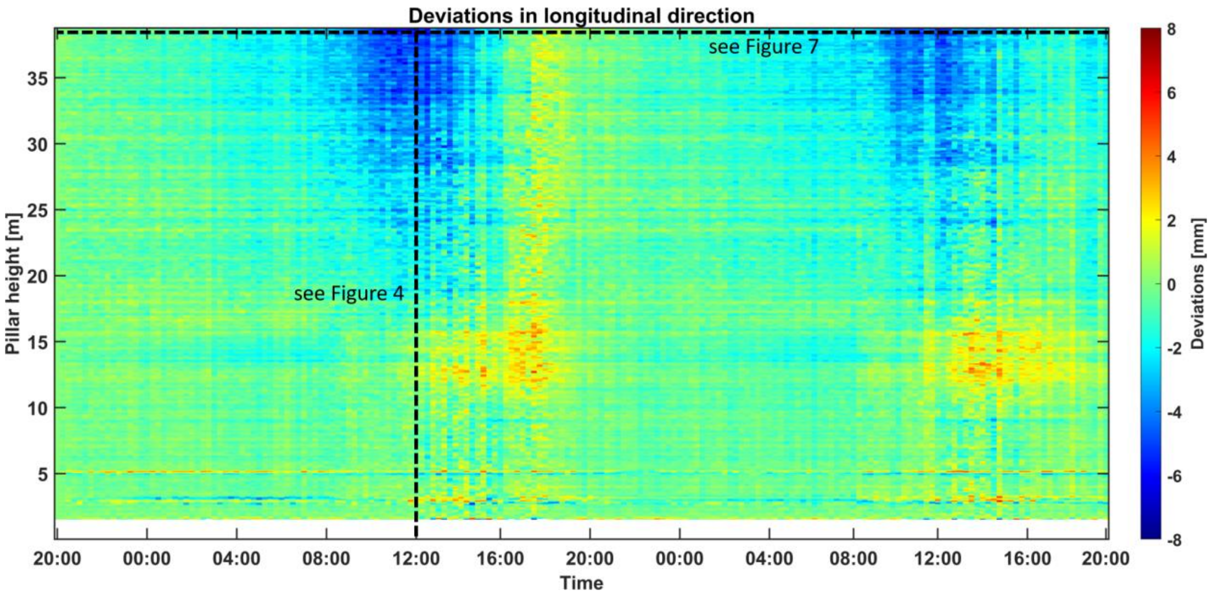

Figure 5. Deformations of pillar 3 in length direction of all measured epochs.

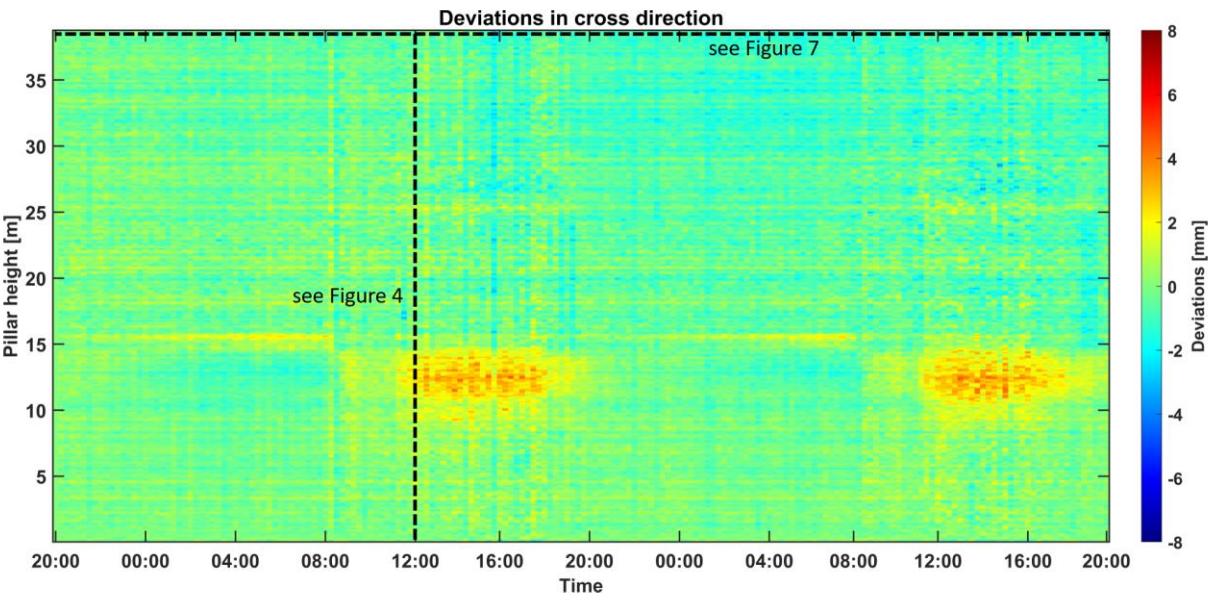

Figure 6. Deformations of pillar 3 in cross direction of all measured epochs.

DOI: 10.3217/978-3-99161-057-1-085

compared with the time series of the prism on top and bottom of the pillar, but also with the calculated displacement by the tilt sensor data assuming a temperature induced bending. These results for both, longitudinal and cross direction can be seen together with the temperature and global radiation during the experiment in Figure 7. The measurement of global radiation is disturbed by the bridge's shadow that is casted onto the radiation sensor from 08:30 to 10:30 for both days. The missing parts are interpolated in Figure 7 (bottom).

The timeline of the prism at the bottom of the pillar shows deformations of less than 0.5 mm in both directions, which could be assumed as stable. The prism on top of the pillar shows a deformation over the day up to 6 mm with its minima at 12:00 at midday. The same deformation with small variations is also captured by the tilt sensor in longitudinal direction. In cross direction, the tilt sensor obviously captures deformations that are not recorded by any other sensor and may be caused by internal temperature dependent effects of the sensor itself but needs further investigation.

The calculated deformation of the point cloud data shows a higher noise than the other sensors in both directions. Nevertheless, the deformation derived from TLS fits well with the measured deformations using the RTS and the prism.

In cross direction, no clear diurnal variation can be seen, except for the tilt sensor. As the pillar is significantly wider in cross direction than in longitudinal direction, this seems to be plausible. Also, no force due to bridge expansion can act onto the pillar in cross direction, whereas the fixed bearing at the pillar may cause additional longitudinal deformations.

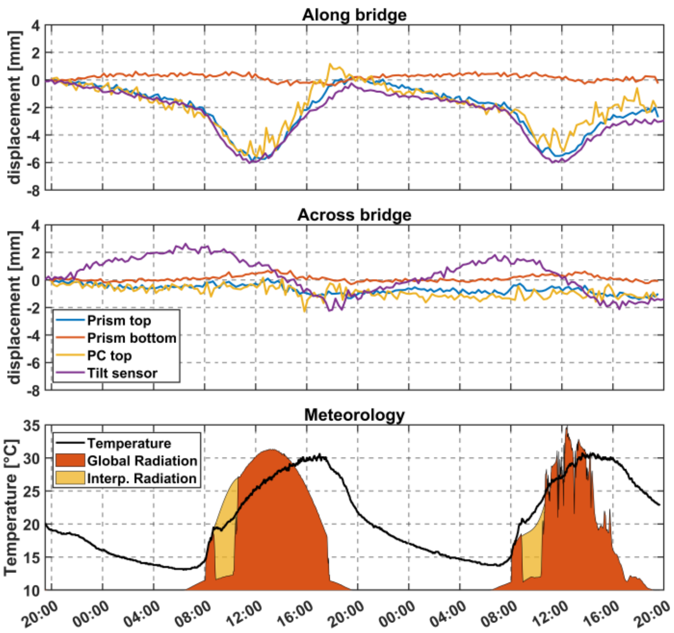

Figure 7. Deformation of the top part of the point cloud (PC), the prism on top and bottom and calculated deformation of tilt sensor on top in length direction (top figure), cross direction (central figure), and the temperature and global radiation during the experiment, while shadow is casted onto the sensor the global radiation is interpolated (bottom figure)

5.2 Gschnitztalbrücke

At the Gschnitztalbrücke multiple measurement epochs were taken, and two of them are shown here. While the comparison of pillar deformations at the Aurachbrücke was motivated by the behavior of the pillar due to one sided sun illumination over a rather short time and high measurement frequency, the concern at the Gschnitztalbrücke is the thermal expansion of the bridge deck and transfer of this deformation to the pillars. Usually the bearings between pillar and girder should absorb this deformation, but as long-term tilt measurements indicated, the bearings do not take the full deformation that is expected by thermal expansion.

In Figure 8, the deformations in plane direction of the pillar can be seen for the spring (2023/05) and summer (2023/08) epochs. The temperature difference between the epochs was only 1°C. Assuming a free thermal deformation of the bridge, and the length of 210 m to the zero point of thermal expansion, the deformation of the girder should sum up to 2.5 mm at the position of the pillar. Figure 8 shows deformations of up to 10 mm and therefore rather bigger deformations than expected.

Looking at the second epoch that is examined in Figure 9, the measured deformations are way bigger with up to 25 mm. The temperature difference on the other hand is 7°C compared to the reference epoch which results in a theoretical deformation of 17.5 mm. So, also in the second epoch, the deformation is way bigger than expected. The shape of deformation can also be seen in the figure and leads from the bottom left to the top right.

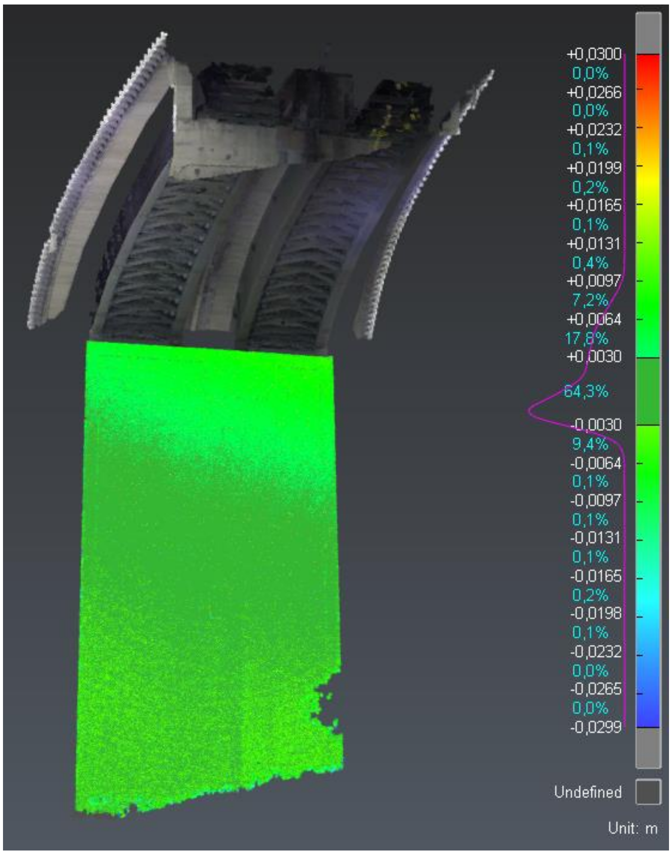

Figure 8. C2C comparison of pillar 6 seen from the end abutment below span 7 of reference epoch 2023/05 and the following epoch of 2023/08

DOI: 10.3217/978-3-99161-057-1-085

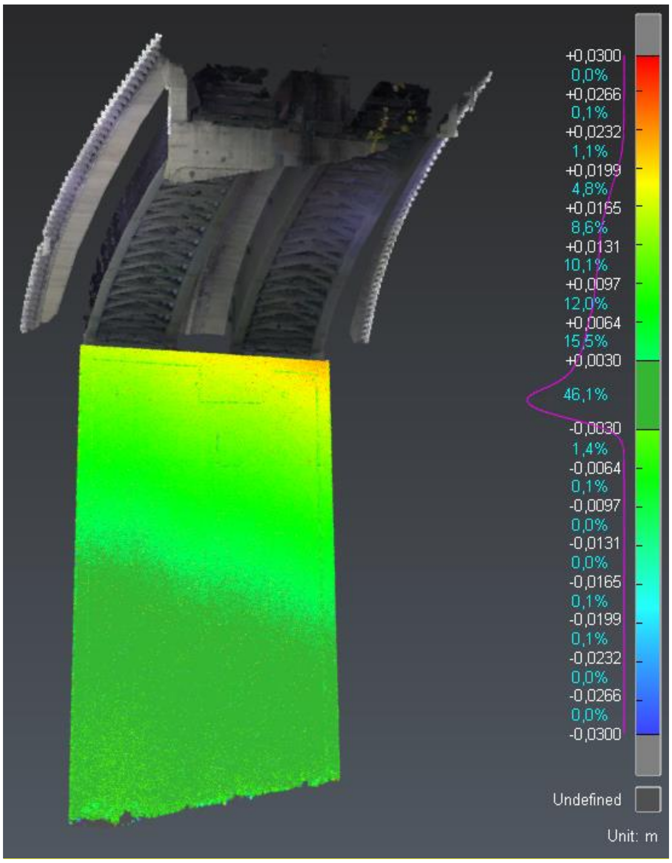

Figure 9. C2C comparison of pillar 6 seen from the end abutment below span 7 of reference epoch 2023/05 and epoch of 2023/11

While both epochs overshoot the expected deformation, the differences of the epoch can also be considered. The temperature difference is 6°C, and therefore a deformation of about 15 mm is expected. Taking the maximum values, which occur on top of the pillar, of 10 mm of the first epoch and 25 mm of the second epoch into account, the relative deformation adds up to 15 mm which is exactly the expected value between the epochs. The offset to the reference epoch has to be investigated further on as its source cannot be determined yet.

The results of the Gschnitztalbrücke show the potential of gathering valid data of the behavior of the structure and verifying the idea of nonconforming bearing transmission over a long period of time.

6 CONCLUSIONS & OUTLOOK

Conventional geodetic monitoring of bridges delivers deformation data only at a few distinct points. With modern laser scanners entire bridge decks and pillars can be observed and a tilting of a pillar can be well distinguished from bending.

The required point clouds can either be captured with full dome laser scanners or scanning total stations. Depending on the given situation the right type of instrument has to be chosen. Although a full dome laser scanner is much faster than a total station, the distance measurement noise is usually higher. Measurements to individual prisms with an RTS still deliver highest accuracy, see Table 1 and true 3D displacements [8].

Table 1. Performance of RTS measurements on prisms [9] and scanning of TLS RTC360 [10]

Instrument	Angle accuracy	Distance Accuracy
MS60 prism measurement	1”	1 mm + 1.5ppm
RTC360	18”	1 mm + 10 ppm

Furthermore, a scanning total station can register point clouds with a high accuracy by using RTS setup functionalities like free stationing.

Overall both techniques help to gain a better understanding of the overall behavior of large civil structures without the need to physically access the measurement location to install sensors on the structure.

ACKNOWLEDGMENTS

We want to acknowledge the support of the Austrian Highway Agency (ASFINAG), for the possibility of performing a load test and taking measurement at their bridges.

REFERENCES

[1] Land Tirol, Verkehr in Tirol Bericht 2023, S. 41, www.tirol.gv.at/fileadmin/themen/verkehr/verkehrsdatenerfassung/downloads/VB_2023_web.pdf, 2024.
[2] T. Moser, W. Lienhart, F. Schill, Static and dynamic monitoring of bridges with contactless techniques. In J. S. Jensen, D. M. Frangopol, & J. W. Schmidt (Eds.), *Bridge Maintenance, Safety, Management, Digitalization and Sustainability: Proceedings of the 12th International Conference on Bridge Maintenance, Safety and Management, IABMAS 2024* (pp. 332-340). CRC Press/Balkema. https://doi.org/10.1201/9781003483755-35, 2024.
[3] F. Schill, C. Michel, A. Firus, Contactless Deformation Monitoring of Bridges with Spatio-Temporal Resolution: Profile Scanning and Microwave Interferometry. Sensors 2022, 22, 9562. https://doi.org/10.3390/s22239562, 2022.
[4] W. Lienhart, F. Schill, T. Moser, Dynamic Bridge Monitoring with Remote Sensing Techniques. In *Structural Health Monitoring 2023: Designing SHM for Sustainability, Maintainability and Reliability* (pp. 184-191). DEStech Publications, Inc. https://doi.org/10.12783/shm2023/36736, 2023.
[5] W. Lienhart, T. Moser, L. Strasser, Large scale monitoring of a highway bridge with remote sensing and distributed fiber optic techniques during load tests. In *Proceedings of the 10th European Workshop on Structural Health Monitoring (EWSHM 2024)* (e-Journal of Nondestructive Testing; Vol. Special Issue). https://doi.org/10.58286/29678, 2024
[6] Y. Yang, C. Holst, Piecewise-ICP: Efficient and robust registration for 4D point clouds in permanent laser scanning, ISPRS Journal of Photogrammetry and Remote Sensing, Volume 227, Pages 481-500, ISSN 0924-2716, https://doi.org/10.1016/j.isprsjprs.2025.06.026, 2025
[7] C. Holst, B. Schmitz, H. Kuhlmann, Investigating the Applicability of Standard Software Packages for Laser Scanner based Deformation Analyses, Proceedings of the FIG working week 2017, ISBN 978-87-92853-61-5
[8] W. Lienhart, Geotechnical monitoring using total stations and laser scanners: critical aspects and solutions, Journal of Civil Structural Health Monitoring, 7(3): 315-324: https://doi.org/10.1007/S13349-017-0228-5Ssf, 2017
[9] Leica Geosystems, Leica Nova MS60 MultiStation Datasheet, 2015
[10] Leica Geosystems, Leica RTC360 Product Specifications, 2018