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Potential of profile laser scanning (PLS) for the application in load tests

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ABSTRACT: The transport infrastructure is reaching in many cases the end of its effective life cycle. The present condition is attributable to a combination of ageing and progressive deterioration as traffic volumes continue to increase. However, it is possible that even recently constructed bridges may already have significant structural damage. Consequently, the maintenance management of existing bridges is becoming increasingly important. However, there is often a lack of up-to-date information on the actual condition of the structures. This is because measuring infrastructure is merely the final stage of the monitoring process, given that tactile sensors are extremely time-consuming and labour-intensive to use. Additionally, due to these principles, measurements can only be taken at a few selected points. The combination of these limitations offers great potential for the use of non-contact profile laser scanning (PLS) in the context of load testing of bridge structures. The structure is scanned with a high-frequency laser beam without the necessity of entering the structure. The spatially distributed displacement measurements obtained in this manner provide a significantly higher density of spatial information about the structure than was previously feasible. Until now, dynamic investigations have been primarily conducted in the domain of profile scanning. This study primarily focuses on static load tests, where spatial resolution and measurement precision can be further enhanced. Two case studies are presented, illustrating non-contact PLS measurements for load testing: one example is on a 160 m arched railway bridge, and the other example is on a steel-concrete composite motorway bridge. It has been demonstrated that a precision of a few tenths of a millimetre can be attained with a spatial resolution in the centimetre range.

KEY WORDS: profile laser scanning (PLS); displacement; bridge monitoring; load testing; SHM; SHMII-13; Full paper

1 INTRODUCTION

Against the background of an ageing infrastructure and the clear trend towards faster trains, higher track utilisation and increasing freight traffic on the roads, reports about the poor condition of the transport infrastructure, decaying bridges and the problems of steel or prestressed concrete bridges from the 1960s and 1970s are becoming increasingly frequent. Damage to newer bridge structures is rarely reported [1], as the quality of planning and execution as well as testing and monitoring should generally ensure appropriate quality.

In order to cover the entire spectrum, two completely different structures are considered in the following:

A motorway bridge from the 1960s, which has basically reached the end of its life due to the enormous freight traffic on the Brenner motorway and the expansion to three lanes per direction. And a railway bridge that is only a few years old and has already suffered massive damage due to manufacturing defects.

What both structures have in common is that assessing the condition of existing bridges is becoming an increasing challenge when important decisions have to be made about cost-intensive replacement or renovation measures, especially if these become necessary after just a few years. In this context, precise knowledge of the actual structural behaviour is a valuable tool for condition assessment, which in many cases can lead to an extension of the remaining service life and thus to considerable benefits for bridge owners and society.

The actual structural behaviour is usually determined by experimental investigations, which may include measurements of accelerations, velocities, strains, inclinations and/or temperatures [2-4]. In addition, displacement measurements based on linear displacement transducers (LVDT) are used to determine relative displacements at abutments [2], between neighbouring superstructures of the same bridge [5] or the width of existing cracks. This type of displacement measurement is possible in principle, as a fixed reference point can be used for the installation of the sensor.

Another important parameter of the structural behaviour would be the absolute vertical displacement of the bridge. This can provide direct information about the actual stiffness of the structure, which in turn can be used in the updating process of the structural model [6, 7].

However, the direct measurement of absolute displacements with classical LVDTs is usually very complex, if not impossible, due to the lack of fixed reference points [4] or because the bridge is simply too high. To close this gap, significant progress has been made in recent years in the field of non-contact displacement measurement. Corresponding sensors enable the measurement of structural displacements without the need to attach sensors to the structure. Suitable technologies for non-contact displacement measurements include terrestrial laser scanning (TLS) [8, 9, 10, 11, 12], laser vibrometer [13, 14], image-based total stations [15], and microwave interferometry [10, 16, 17, 18].

Compared to other non-contact measurement techniques, which only allow measurements at one point, TLS or profile laser scanners (PLS) can also be used to perform spatially distributed measurements. The spatial resolution offers the

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advantage that larger areas of the structure can be monitored with only one sensor, allowing a deeper understanding of the structural response in an efficient way.

This study expands the application of PLS by demonstrating its capability for dense, high-precision deformation monitoring on two large-scale bridges under static loading. The novel aspects include the spatial resolution achieved, the scale of the structures examined, and a worst-case precision evaluation strategy, which has not been systematically addressed in previous studies.

Before going into more detail on TLS and in particular its use as a PLS for dynamic and static load tests in section 3, the two investigated bridges are presented in section 2.

2 INVESTIGATED BRIDGES AND PERFORMED LOAD TESTS

As mentioned in Section 1, the following section presents load tests on two quite different bridges, which will first be discussed in more detail in this section.

2.1 Motorway bridge

The Austrian Brenner motorway is part of the European route E45, which crosses Europe in a north-south direction from northern Finland to southern Italy. The Alpine crossing in Austria is an important part of the route and is also crucial for cross-border freight transport in Europe. The motorway route across the Alps was mainly built in the 1960s, and the bridge under investigation was also built during this period.

Fig. 1: View of the motorway bridge: span 7.

The bridge was originally designed for two lanes in each direction, but a third lane was added in the 1980s due to the increasing amount of traffic. However, the basic load-bearing structure of the bridge has remained essentially unchanged over the years. As an important part of a European transit route, the structure must therefore be carefully monitored.

The structure itself consists of a steel-concrete composite construction and is designed as a 7-span continuous girder, with the outer spans having a length of 70 m and all other spans having a length of 84 m. The total length is therefore 560 m.

Part of this monitoring strategy was a load test, which was carried out in May 2023. One direction of travel on the motorway bridge was temporarily closed in order to place two trucks, each weighing 50 tonnes, on the bridge to create different load scenarios. In addition, four quasi-static tests were carried out.

The profile laser scanner measurements focussed on the outermost span (span 7) next to the southern bridge abutment, as shown in Figure 1.

In addition to the profile scanner, 3D TLS [19, 20, 21], fibre optic sensors [19, 21, 22], dynamic and static total stations [19, 20, 23], a terrestrial microwave interferometer, modular digital camera total stations [24], GNSS [21] and acceleration sensors [21] were used.

2.2 Railway bridge

The railway bridge is a 370 m long double-track railway overpass designed as an arch bridge. The longest span is 165 metres. The track is up to 71 m above the valley floor and is straight in the construction area at a design speed of 300 km/h, see Figure 2.

Fig. 2: View of the railway bridge.

The bridge structure has only been under traffic for a few years and already shows significant construction-related damage. In the course of the structural inspection, structural defects and concrete spalling were initially recognised and appropriate repair measures were planned. During the repair work, it turned out that the gravel pockets and the severe segregation of the structure were not only localised, but affected large areas of several square metres, see Figure 3.

Fig. 3: Damaged area with heavily segregated concrete structure.

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The damage is due to segregation and washing out processes during concreting. In order to determine the full extent of the damage, structural diagnostics were carried out on the entire arch bridge. The investigations confirmed the assumptions regarding the poor concrete quality of the arch concrete. The results raised questions about the serviceability and stability of the structure under traffic.

As a mathematical analysis of the damage alone was not conclusive, the owner decided to carry out a load test. The static load test was carried out with five locomotives with a total weight of 550 tonnes in various load positions. In order to be able to determine the deformations under the applied load as simple and reliable as possible, a non-contact PLS was used.

3 TERRESTRIAL LASERSCANNING (TLS)

TLS such as the Z+F IMAGER 5016 make it possible to digitise the entire environment in a 360° panorama in the form of a 3D point cloud. During the scanning process, a high-frequency rotating mirror deflects the laser beam and the TLS also rotates around its vertical axis. This sequential recording process produces a high-resolution point cloud of the visible environment, see Figure 4.

The non-contact distance measurement of the Z+F IMAGER 5016 works according to the AMCW method (Amplitude Modulated Continuous Wave). To obtain the absolute distance value, the phase shift between the reflected and emitted signal is used, which is induced by the light path in the intensity-modulated periodic signal. To resolve the phase ambiguities and thus determine the absolute distance, several wavelengths are modulated onto the carrier wave. In addition, the user is provided with the amplitude (intensity), which represents the ratio of emitted to received energy, see grey scales in Figure 4.

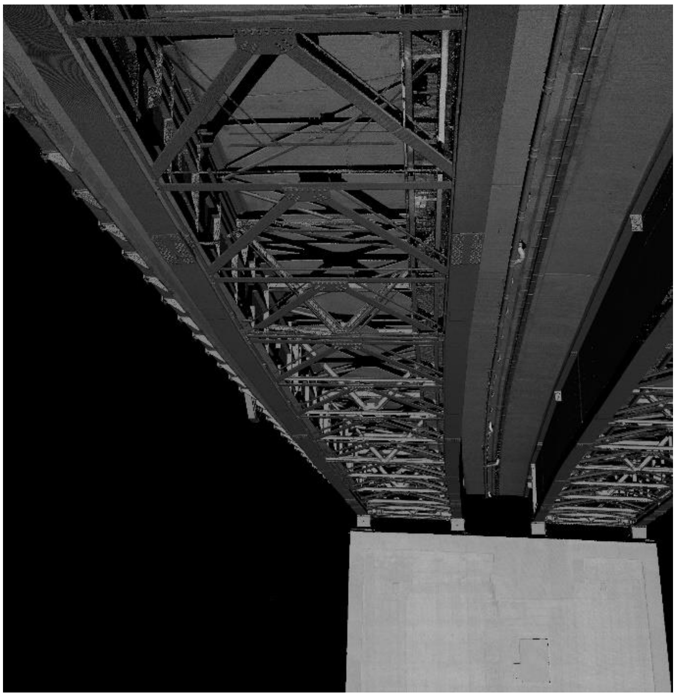

Fig. 4: Extract from the 3D point cloud of span 7 of the motorway bridge. Intensity values are shown as grey scales.

In principle, the measurement method is characterised by a very high spatial resolution, but in turn only allows a low temporal resolution. In addition, the single point precision is in the millimetre range and is therefore not sufficiently accurate for most monitoring applications.

3.1 Profile laser scanning (PLS) dynamic

In contrast, a profile laser scanner (TLS in profile mode, 2D) [8, 10, 25, 26] only uses the high-frequency rotating deflection mirror, but there is no rotation around the standing axis, see diagram in Figure 5 and section of a profile in Figure 6.

Fig. 5: Schematised representation of PLS.

As special properties of the sensor are important for bridge monitoring applications, these are explained in more detail in the following.

3.1.1 Measuring Frequency

The usable measurement frequency for deformation monitoring of bridges with the Z+F IMAGER 5016 in profile mode depends on the rotation speed of the deflection mirror, which is up to 55 Hz. It should be noted that there is a relationship between temporal and spatial profile resolution: at the same laser measurement rate, doubling the measurement frequency halves the spatial resolution.

3.1.2 Measurement Precision

The precision of the measurement depends significantly on the energy reflected back from the structure and thus on its backscattering properties in the corresponding wavelength band, since the phase measurement precision is directly coupled to the signal-to-noise ratio (SNR) of the reflected signal [27].

For the Z+F IMAGER 5016, as is common practice in the TLS field, the manufacturer provides range measurement standard deviations for different surface reflectivities and ranges. These are based on a fixed laser measurement rate of 127 kHz and range from 0.2 mm to just under 10 mm.

However, these accuracy specifications are not very meaningful in practice and only cover a very small range of applications: The specified reflectivity of the structure to be measured is usually not known and can also vary spatially. In addition, the measurement geometry plays a crucial role in the specification of realistic measurement uncertainties; it is partly responsible for the occurrence of predominant forward reflection, i.e. the shallower the angle of incidence, the greater the potential for forward reflection and low SNR. The

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measurement geometry is also critical for the derivation of the projected vertical deformations. Furthermore, no reflectors are to be used in the application scenario considered, so an accuracy specification based on a defined reflector is not meaningful.

For TLS in general, the stochastic modelling of the range measurement based on the registered intensities [28,29] is possible and allows a practical (insitu) determination of the range precision. This approach takes into account all effects affecting the measurement process (surface reflectivity, measurement geometry, atmosphere, etc.).

3.1.3 Spatial Resolution

With the Z+F IMAGER 5016 the range is part of the raw measurement. The range resolution is 0.1 mm and is defined by the size of the modulated fine scale used in combination with the implemented phase measurement.

The actual spatial resolution of a profile scanner is defined by the rotation speed of the deflection mirror, the laser measurement rate and the divergence angle of the laser beam. The actual spatial resolution is usually lower than the angular resolution specified by the manufacturer for two reasons:

- Depending on the choice of parameters, the laser spots of successive measurements overlap to a greater or lesser extent, which reduces the actual resolution on the surface of the structure.
- The rotational speed causes an additional deformation of the laser footprint in the profile direction (elongation), as a corresponding angular range is always covered during the measurement time. This can be interpreted as a larger "true" divergence angle or as an increasing overlap of successive measurements according to [30, 31].

Another aspect when considering the spatial resolution actually available in practical applications is that the single-point precision of a PLS is usually not sufficient for the requirements of the application scenario [8]. Therefore, in order to achieve the required precision, an averaging of neighbouring measurement points is performed (class formation), which further reduces the spatial resolution of the profile scanning in favour of a qualitatively better derivation of displacements.

Two examples are given below to give an idea of the spatial resolution that can be achieved:

- 20,000 points are measured per profile at a measurement frequency of 55 Hz, which corresponds to a theoretical angular increment of 0.018°. If 75 adjacent points are combined (class formation, see colour coding in Figure 6), the actual available angular increment is reduced to 1.35°, which corresponds to a spatial resolution of 0.24 m at a distance of 10 m.
- If the measurement frequency is reduced to 14 Hz, 80,000 points are measured per profile and a spatial resolution of 0.06 m at a distance of 10 m is achieved.

Depending on the measurement geometry, deformation time series with a precision in the sub-millimetre range can be derived from the spatially distributed time series generated in this way.

Compared to other measurement techniques for monitoring applications, which only allow measurements at a single point, PLS thus also allow a spatially distributed recording of the structural response. The spatial resolution offers the advantage that larger areas of the structure can be monitored and verified with a single sensor, which enables a deeper understanding of the structural response in a very efficient way.

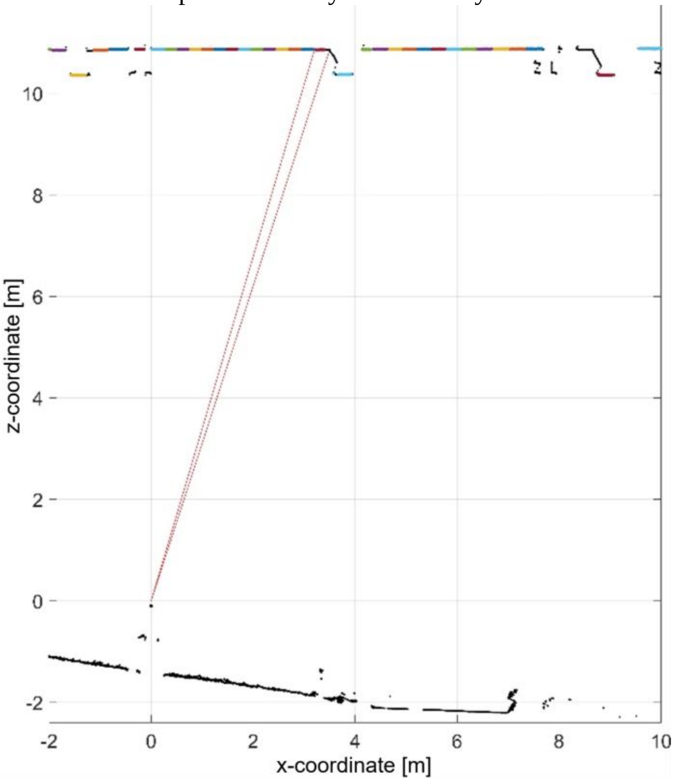

Fig. 6: Extract from profile measurement, with coloured representation of class formation.

3.1.4 Projection of displacements

The purpose of using a PLS for deformation monitoring of bridges is to obtain deformations in a defined direction (usually vertical or horizontal). Therefore, the "raw" measurements need to be projected in the desired direction. For projection, it is usually assumed that the vertical displacement of a bridge is dominant, while possible horizontal components are considered negligible. Since the raw measurements of a profile scanner consist of distance and internal angle measurements, the projection of deformations is inherent and possible with high accuracy. The manufacturer specifies an angular accuracy of 0.004° for the Z+F IMAGER 5016. The horizon reference is provided by an internal dynamic compensator which operates in the same accuracy range as the angle encoders. The dynamic compensator also detects and corrects for low frequency movements of the sensor during the measurement.

Up to this point, it has been assumed that there is only vertical displacement of the bridge structure due to an applied load. However, it is possible that there is an additional horizontal displacement component. As the PLS is a 2D sensor, these can be measured directly at suitable locations (vertical areas) if the displacement is in the profile direction.

3.2 Profile laser scanning (PLS) static

For use in static load tests, the temporal dimension plays a subordinate role, but in static profile laser scans the precision and spatial resolution can be further increased by additional temporal averaging during the load retention phases.

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With a load retention phase of 5 minutes, at least 4,200 profiles are measured. This corresponds to 315,000 individual measurements in the example defined above with 75 points per class and profile that can be used for further derivation of the measured values, which enables a significant increase in precision.

The major challenge in static load tests with profile laser scanners is to keep the external conditions constant so that, for example, no tilting of the tripod occurs, e.g. due to solar radiation or unstable ground. TLS, like almost all non-contact measuring sensors, are sensitive to atmospheric conditions, which in extreme cases, e.g. due to rain or fog, can completely prevent measurement.

4 QUASI-STATIC LOAD TEST

For quasi-static load tests, the speed at which the load (truck or locomotive) passes over the measurement object (bridge) is usually kept low in order to minimise dynamic effects that could falsify the result. This is in favour when using profile scanners, as the overall measurement rate of approximately 55 Hz is not comparable with conventional sensors and the spatial resolution has to be reduced at higher repetition rates.

Accordingly, it makes practical sense in these cases to use the lowest repetition rate of 14 Hz, as this allows up to 80,000 points per profile to be measured and maximises the spatial resolution.

For the two sample bridges, a quasi-static load scenario was only carried out for the motorway bridge, which is why this section focuses on the measurements at the Brenner Pass.

The quasi-static load test was performed with two trucks of 50 tonnes each, which crossed the entire bridge directly one behind the other at a speed of 5 and 30 km/h respectively. The position and speed of the two trucks were monitored using GNSS so that the resulting displacements could be synchronised with the position of the trucks.

The measurements with the PLS took place in span 7, the scanner was located approx. 13 m below the bridge and a main girder was measured. As the bridge is located in a curve, the horizontal measuring range on the main girder was limited to approx. 50 m of the total span length of 70 m due to the curvature of the bridge.

In this case, approx. 75 measuring points are averaged per class, so that ultimately 117 classes, i.e. 117 spatially distributed displacement time series can be derived, whose standard deviations are in a sector around 0.1 mm. The standard deviation tends to increase towards the edge due to the deteriorating geometry.

Figure 7 shows a section of the measurement results for a crossing at 5 km/h. In the upper diagram, a time series approximately in the centre of the field is shown in black. In addition, three coloured markers show the times at which the two trucks are located in the middle of span 5 (blue), in the middle of span 6 (red) and in the middle of span 7 (yellow). The design of the bridge as a continuous girder is evident here, as the measured span (span 7) already reacts to the loads in the other spans and rises or falls accordingly.

This representation as a time series based on just a single analysed class corresponds to the result that an LVDT would provide.

In the lower diagram in Figure 7, the points in time marked in different colours (trucks on span 5, span 6, span 7) are shown in full spatial resolution with 117 classes in the corresponding colour. The PLS enables the evaluation of the bending line for the entire scanned field section at any point in time.

The data gap in the centre of the diagram is caused by a combination of installed sensors (cabling) and a reinforced, heavily bolted area (see Figure 4 in the centre of the main girder).

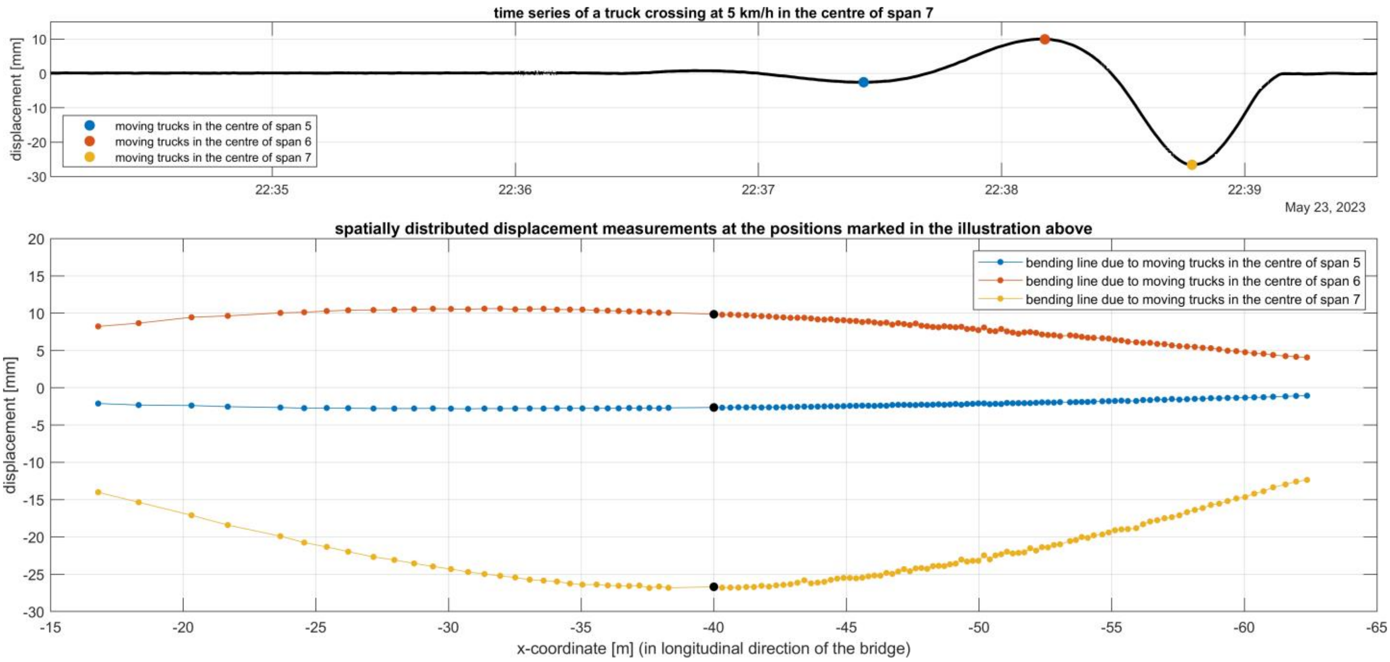

Fig. 7: Exemplary results of the evaluation of a quasi-static load test: In the upper diagram a simple pointwise time-displacement representation can be seen, while the lower diagram shows the potential of profile scanning, as a bending line can be analysed over the entire visible area at any point in time.

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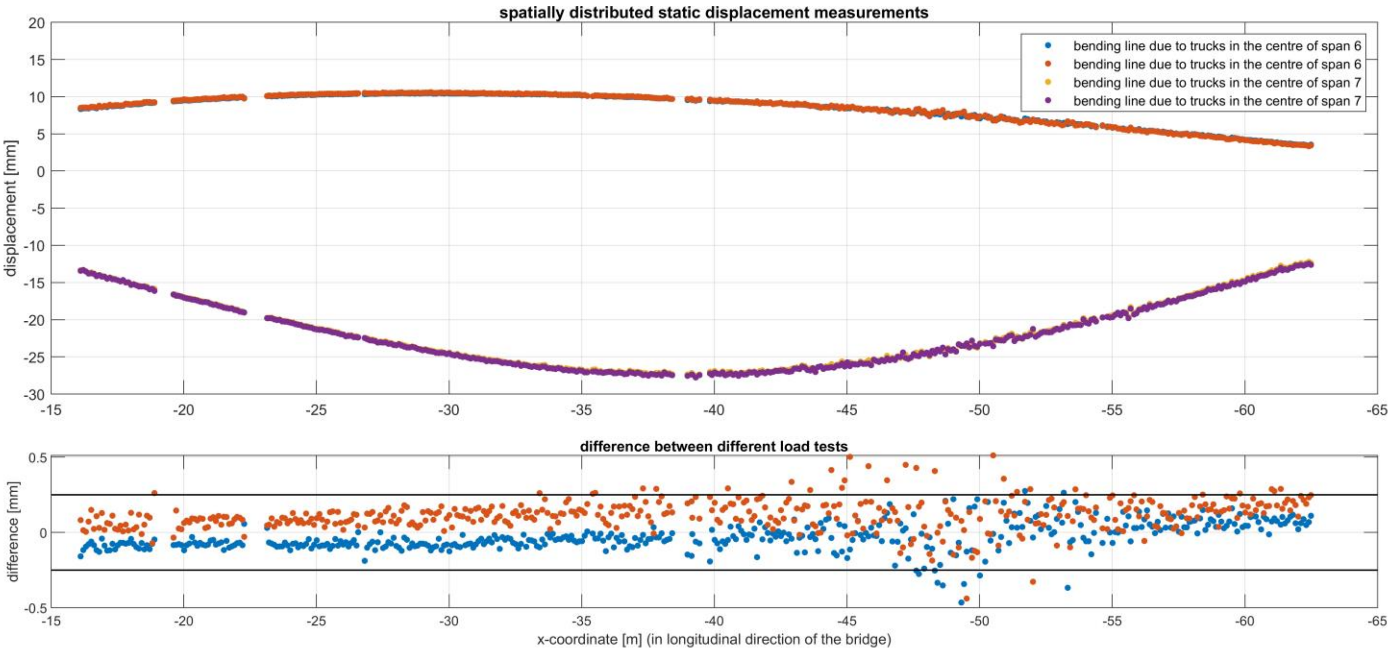

Fig. 8: Results of the evaluation of four static load tests: In the upper diagram, the bending lines of the two load positions are each shown twice. The lower diagram shows the differences between the respective tests and provides an estimate of the achievable precision of the measurements using profile scanning.

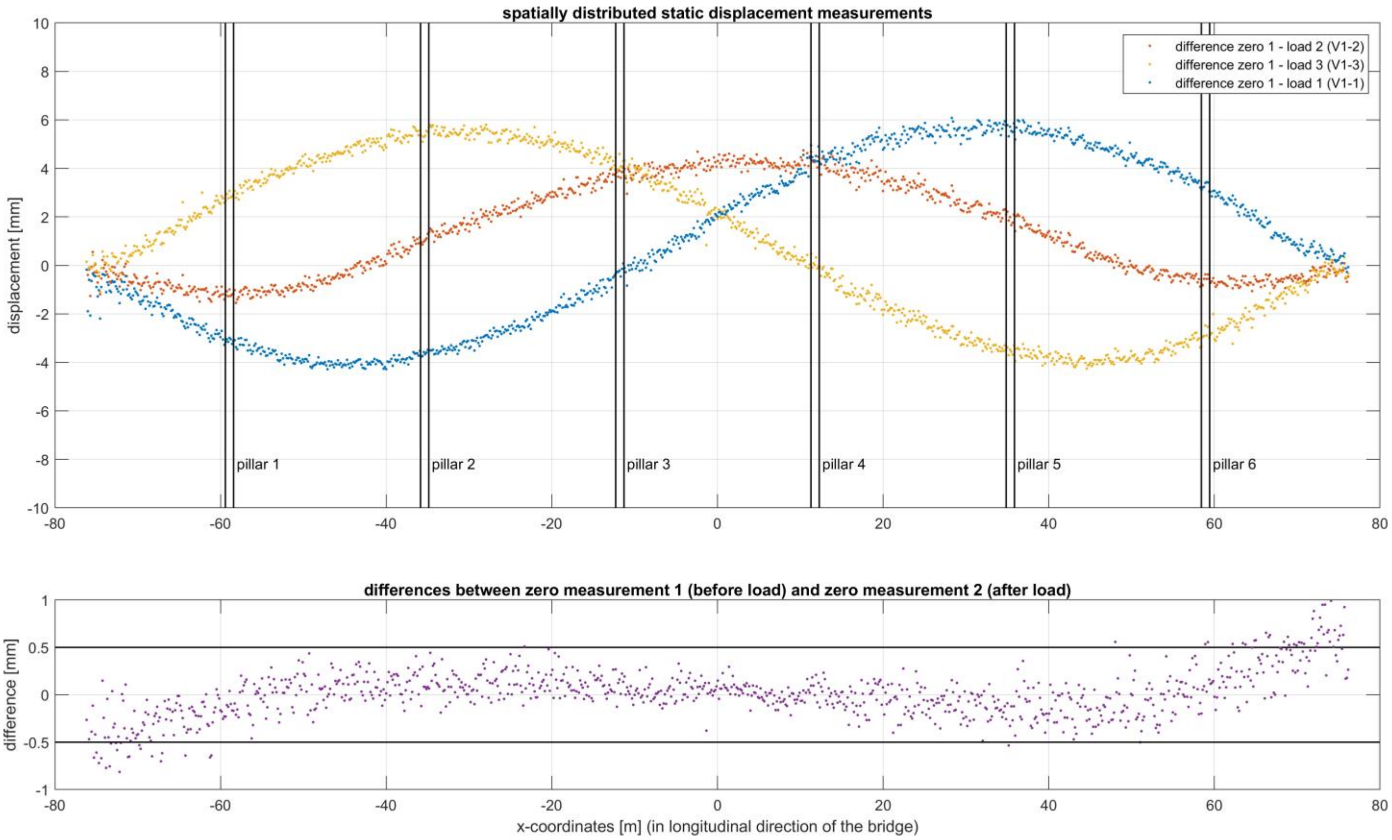

Fig. 9: Results of the evaluation of three static load positions: The upper diagram shows the bending lines induced by the load positions. The lower diagram shows the differences between two independent zero measurements (bridge without load) before and after the actual measurements.

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5 STATIC LOAD TESTS

A static load test was conducted on both structures: This entailed the deployment of two trucks (with a total weight of approximately 100 tonnes) on the motorway bridge and five locomotives (with a total weight of approximately 550 tonnes) on the railway arch bridge. For each bridge different load configuration where tested and the structural response was measured using static profile laser scanning (PLS).

As outlined in Section 3.2, the enhanced spatial resolution in static profile scanning enables a measurement point spacing of 10 cm across the full scan range in both cases. This enabled the acquisition of over 400 spatially distributed displacement measurements on the motorway bridge and almost 1000 on the railway bridge (see upper diagrams in Figures 8 and 9). Those diagrams illustrate the measured displacements for the various load configurations, which are colour-coded according to the load configuration. As illustrated in Figure 7, analogous data deficiencies have been observed to occur due to external factors such as sensor interference or bolted connections.

In comparison with previous PLS applications, this study introduces a significantly higher density of measurement points on large-scale infrastructure due to the use of static PLS and demonstrates the feasibility of applying PLS as a primary deformation measurement technique during full-scale static load tests.

In order to provide further illustration of the precision potential of static PLS, two novel evaluation strategies were applied: For the motorway bridge (see Figure 8), a comparative analysis of repeated load positions was conducted (see lower diagram). For the railway bridge (see Figure 9), the evaluation is based on two independent zero measurements (see lower diagram). It is important to note that both approaches provide a conservative estimate of measurement precision under realistic test conditions. This is due to the fact that they account for potential systematic effects, such as slight variations in load positioning or residual structural deformations.

Despite the presence of these influencing factors, the deviations between the individual tests for the Brenner motorway remain predominantly below 0.25 mm, with systematic offsets of 0.1 mm and 0.05 mm, respectively, as previously described.

For the measurements at the railway bridge, a vertical precision of 0.5 mm was specified in the area of the piers (-60 m to 60 m) that support the track on the arch. As illustrated in the lower diagram of Figure 9, this order of magnitude could be sustained. The deviations exhibit a slight increase towards the edge, a phenomenon that can be attributed to the substantial dimensions of the structure and the deteriorating measurement geometry towards the edge. Furthermore, a discernible residual systematic remains identifiable in the observed discrepancies, potentially attributable to residual deformation of the bridge arch. Irrespective of the underlying cause, this further distorts the precision estimate, thereby leading to the expectation of even better results.

For the profile scanning and load retention phases, a duration of five minutes was deemed adequate for both bridges. Consequently, a test involving three load retention phases and double zero measurement could be conducted in approximately 30 minutes under optimal conditions. However, it was necessary to deviate from this ideal procedure for the two static load tests. It was determined that load retention phases of 10 minutes would be implemented on the Brenner motorway, a measure necessitated by the substantial deployment of individual sensors (see Section 2.1).

In the case of the arch bridge, only profile scanning was used and a load retention phase of 5 minutes was planned, although this had to be extended in some cases due to fog passing through.

6 CONCLUSION

Compared to conventional sensors, PLS can be used to obtain a large number of spatially distributed measurements with just one sensor, which enables an extremely efficient measurement and also a previously unimaginable understanding of the structural reaction.

Even for the quasi-static load test, it was possible to derive over 100 spatially distributed displacement time series over a range of almost 50 metres. The analysable range of the section was not limited by the sensor, but by the radius of curvature of the bridge.

Implementing static load tests enhances spatial resolution by enabling the temporal averaging of additional measurement data. This assertion is substantiated by the case study of the railway bridge, in which the deformation of the entire 160 metre arch was captured using almost 1,000 measurement points. Despite challenging environmental and structural conditions, sub-millimetre precision of up to 0.5 mm was achieved in the critical areas.

Unlike previous PLS applications, this study uses static PLS as the primary measurement method for full-scale static load tests on large infrastructure. The high density of measurement points, over 400 on the motorway bridge and almost 1,000 on the railway bridge, enabled detailed, spatially resolved deformation analysis for various load configurations. To assess measurement precision under realistic conditions, two innovative evaluation strategies were employed. The first involved repeated load configurations on the motorway bridge and the second involved two independent zero measurements on the railway bridge. Both approaches yielded conservative estimates of precision, which is advantageous when accounting for systematic effects such as variability in load placement and residual deformations.

The findings demonstrate not only the technical feasibility of static PLS in such scenarios but also its robustness under non-ideal conditions, including sensor interference, structural complexity, and environmental influences such as fog. The study demonstrates the potential of static PLS for precise, efficient, and large-scale deformation monitoring in structural testing contexts.

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