TERRESTRIAL LASER SCANNING FOR DEFORMATION MONITORING - LOAD TESTS ON THE FELSENAU VIADUCT (CH)

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ABSTRACT:

In conjunction with future renovation work on the 33-year-old Felsenau viaduct (CH), which is part of the Swiss highway A1 and one of the most remarkable concrete bridge structures in Switzerland, load tests were performed for evaluating the fatigue resistance and refining the analytical models. The bridge girder was therefore loaded with more than 100 tons. The Institute of Geodesy and Photogrammetry at ETH Zurich was responsible for deformation monitoring during the load tests. In addition to traditional surveying methods such as precise levelling and tacheometry, terrestrial laser scanning was performed for the detection of deformations. This paper presents unique load tests on the Felsenau viaduct as well as results of deformation monitoring with focus on measurements by terrestrial laser scanning. Furthermore, a comparison of terrestrial laser scanning and precise levelling is described.

KURZFASSUNG:

Im Zusammenhang mit zukünftigen Renovationsarbeiten am 33-jährigen Felsenau-Viadukt (CH) wurden Belastungsversuche zur Untersuchung von Ermüdungsproblemen und zur Verbesserung der Berechnungsmodelle durchgeführt. Der Felsenau-Viadukt gehört zur schweizerischen Nationalstrasse A1 und gilt als eines der markantesten Betonbauwerke der Schweiz. Der Viadukt wurde mit mehr als 100 Tonnen belastet. Das Institut für Geodäsie und Photogrammetrie der ETH Zürich war für die Bestimmung der Deformationen verantwortlich. Neben traditionellen Messmethoden wie Präzisionsnivellement und Tachymetrie wurde auch terrestrisches Laserscanning für die Bestimmung der Deformationen eingesetzt. Im Folgenden werden dieser einzigartige Belastungsversuch sowie die Resultate der Deformationsmessungen vorgestellt. Dabei liegt der Fokus auf den Messungen mittels terrestrischem Laserscanning. Ebenso werden die Resultate der Messungen mittels terrestrischem Laserscanner und Präzisionsnivellement miteinander verglichen.

1. INTRODUCTION

The Felsenau viaduct of the Swiss highway A1 is situated north of Berne, the Swiss capital. The average daily traffic on the six-lane viaduct is about 100'000 vehicles. Trucks represent an important part of all vehicles. Furthermore, rush hour peaks are significant due to traffic generated by the city of Berne. The 33-year-old viaduct has a length of 1116 m and traverses the Aare valley at a height of up to 60 m (Figure 1). This viaduct is a span bridge made of concrete and is one of the most remarkable bridge structures in Switzerland. The carriageway lies on cantilever slabs with 26.2 m wide cross-sections. Additionally, piers with cross-sections of about 7.5 m carry the slabs. The span length of the viaduct between piers is up to 156 m for the large middle sections.

In conjunction with an overall renovation of the tangential highway north of Berne, the Felsenau viaduct was subject to detailed investigations. Due to a large rising of the traffic volume within the last years, the viaduct does not fulfil the safety requirements any longer. Furthermore, the transversely prestressed cantilever slabs may suffer from fatigue problems. In order to obtain a reliable basis for the evaluation of the fatigue resistance and to refine the analytical models, additional load tests were performed on the Felsenau viaduct. While loading the viaduct, the arising deformations were monitored and the results were valuable for further analyses.

For two nights in spring 2007, the Felsenau viaduct was closed for traffic, and load test were performed. Two tanks with an approximate weight of 54 tons each were used to load the cantilever slabs. The Institute of Geodesy and Photogrammetry at ETH Zurich (IGP) was responsible for the monitoring of the Felsenau viaduct with regard to deformations. Besides traditional surveying methods as precise levelling and tacheometry, terrestrial laser scanning (TLS) was established for the detection of potential deformations of the viaduct, of the cantilever slabs in particular.

Until now, TLS has been introduced for deformation monitoring of different applications in the field of engineering geodesy. (Tsakiri et al., 2006) discuss the possibilities of TLS for deformation monitoring in general and compare the monitoring of selected targets with the area-wide monitoring. The main advantage of deformation monitoring by TLS is the full surface representation. A discretisation of the object by reference points is not required. This enables the detection of unexpected deformations.

Deformation monitoring by TLS has been accomplished for several projects as in tunnels, e.g. (Lindenbergh et al., 2005)

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and (van Gosliga et al., 2006), at large dams, e.g. (Grimm-Pitzinger and Rudig, 2005) and (Zogg and Schulz, 2007), and at lock gates, e.g. (Schäfer et al., 2004) and (Hesse and Stramm, 2004). Furthermore, deformation monitoring for structural deformation measurements of a concrete and timber beam is described in (Gordon et al., 2004).

Figure 1. Felsenau viaduct, completed in 1975.

Main objectives of the deformation monitoring by TLS on the Felsenau viaduct were on the one hand to get to know the advantages and limits of the new measurement technology for load test in the field of bridge monitoring, and on the other hand, a comparison with precise levelling should point out the possibilities of TLS with focus on the measurement accuracy and detection of deformations.

In section 2 of this paper, the load tests are described as well as the geodetic instruments which were used for the load tests. Section 3 deals with processing of the TLS data and section 4 compares the results of TLS and precise levelling. Finally, section 5 discusses the results, and conclusions are given in section 6.

2. LOAD TESTS

For the load tests, the Felsenau viaduct was closed for traffic in order to minimize vibrations of the bridge girder. The traffic was diverted. Several parties were involved for the proper accomplishment of the tests, i.e. the Office of Civil Engineering of the Canton of Berne, the Federal Traffic Office, a local engineering company, and the ETH Zurich. The Institute of Structural Engineering at ETH Zurich had the technical lead. The IGP was responsible for the geodetic measurements.

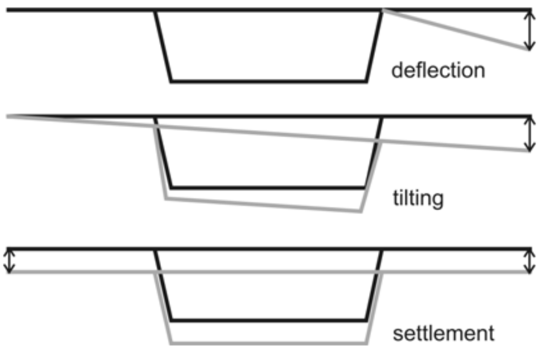

Figure 2. Expected deformation behaviours of the cantilever slabs and bridge girder under loading.

2.1 Initial situation

The load tests were performed during two nights when the weight was positioned on different sections of the viaduct. Two tanks, each weighting approximately 54 tons, were used as a load. The load tests were performed at several sections of the viaduct. The descriptions and analyses below refer to the first night when the weight was positioned in the middle section of the viaduct. The span length and the height were 156 m and 60 m respectively.

The load was positioned on the northern outer side of the prestressed cantilever slabs (Figure 5). Hence, deformations were expected as a deflection of the cantilever slab and a tilting and settlement of the bridge girder (Figure 2). The deflection of the cantilever slabs were of main interest for the civil engineers.

The procedure of the load test was scheduled in four main steps: initial measurement, loading P1 with one tank, loading P2 with two tanks, final measurements P3 without any load. Recovery periods of about 30 minutes represented an important aspect. They allowed the viaduct to relax and to minimize the vibrations and oscillations caused by the traffic, respectively by the tanks. This was a very important aspect for the precise levelling due to the fact that sensitive levelling compensator would not work under oscillating movements of the underground. The measurements of the deformations were performed with a tacheometer, a precise level and a terrestrial laser scanner.

2.2 Terrestrial laser scanning (TLS)

For the measurements by TLS, the terrestrial laser scanner Imager 5006 by Zoller+Froehlich (http://www.zf-laser.com) was chosen (Figure 3). The choice was based on the scanning speed of about 500’000 points per second, the measurement accuracy and the availability of the instrument. According to specifications by the manufacturer, the range noise is about 2.0 mm in a distance of 25 m and a target reflectivity of 20% (dark-grey target). The scans were performed on the bridge girder of the Felsenau viaduct. The carriageway surface was dark-grey due to the asphalt. Furthermore, the time for a scan was an essential factor due to a tight schedule of the load tests. The measurements had to be planned für a minimum closing time of the viaduct for traffic.

Figure 3. Terrestrial laser scanner Imager 5006 by Zoller+Froehlich (http://www.zf-laser.com).

2.3 Precise levelling

The precise levelling was performed with the Trimble DiNi digital level (http://www.trimble.com) and an invar precision bar code levelling-staff. The a priori-accuracy (1σ) for the height measurement is set to 0.3 mm per 1 km of double levelling. Due to the night-time measurements, the invar precision bar code levelling-staff had to be lighted by a floodlight to enable the measurements by the precise level (Figure 4). The precise levelling was established to measure absolute vertical displacements of the bridge girder.

Figure 4. Precise levelling of reference points on the viaduct.

2.4 Tacheometry

The measurements by the tacheometer were performed from the valley floor at a distance of about 150 m from the object. Prior to the load test, bolts for tacheometer prisms were installed underneath the cantilever slabs and the lower slab of the box girder. This enabled the measurement of profiles of the bridge girder. The main purpose of the tacheometer measurements was to provide an additional measurement method to the precise levelling and the detection of special deformation behaviours of the bridge superstructure. The measurements by tacheometer are not further analysed or discussed below.

2.5 Measurement setup

Due to the large height of the bridge girder above ground (approximately 60 m), the measurements by the terrestrial laser scanner as well as the precise levelling were performed on the Felsenau viaduct. Prior to the load tests, measuring bolts were embedded into the deck slab. In advance, short rods could be screwed on the bolts during the load tests. The bolts were connected with the concrete slab through the asphalt.

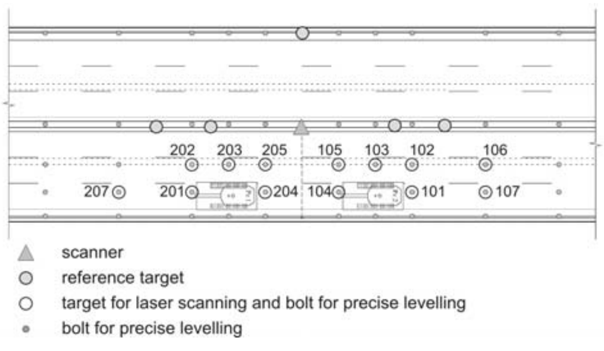

Figure 5. Measurement setup for terrestrial laser scanner and targets for TLS and precise levelling.

For the precise levelling, more than 40 bolts with the respective short rods were set up (Figure 5). The bolts were measured by precise levelling for each period of the load tests as well as for the initial situation. Furthermore, an additional precise levelling was measured each time between the test area and a height transfer reference outside of the Felsenau viaduct. This was essential for the detection of bridge girder settlements.

The terrestrial laser scanner Imager 5006 was placed on a heavy tripod in the middle of the bridge girder (Figure 3). The heavy tripod was used to reduce possible movements and torsions of the tripod. The height of the tripod was set to approximately 2 m to minimize small angles of incident of the laser beam on the surface. Nevertheless, small angles of incidence could not be avoided due to the large extensions of the test area. In addition to the Imager 5006, five reference targets were setup for registration purposes of the 3D-point clouds. Hence, four reference targets were setup as well in the middle of the bridge girder, and the fifth reference target was established on the opposite side of the test field on the cantilever slabs (Figure 5). The maximum range from the scanner to the reference targets was about 17 m. White spheres made of wood with a diameter of 15 cm were used as reference targets.

In addition to the reference targets, further targets were set on several bolts or short rods, which were used for the precise levelling. The additional targets are labelled in Figure 5. The targets were coated spheres made of Styrofoam with a diameter of 12 cm. These additional targets were mainly established for the analyses of the relation between the measurement of precise levelling and TLS.

Generally, the scans were performed with the scanning resolution “high” (0.036° for horizontal and vertical angular resolution) and the targets were additionally scanned with the resolution “superhigh” (0.018° for horizontal and vertical angular resolution). Due to the relative deformation monitoring of the Felsenau viaduct by TLS, only cantilever slider deflections were expected to be detected. Tilting and settlements of the bridge girder could not be monitored by the presented measurement configuration by the terrestrial laser scanner. An absolute height reference was needed for the detection of absolute bridge girder deformations.

3. PROCESSING TLS DATA

Processing the TLS data included the registration and filtering of the 3D-point clouds as well as the determination of deformations by comparing the 3D-point clouds with load on the Felsenau viaduct to the initial situation. For the analyses, an area-wide deformation analysis and a discrete analysis with respect to targets on the object were carried out. The carriageway, i.e. the cantilever slabs were scanned up to a range of 20 m from the station of the terrestrial laser scanner. The maximum distance for the measurements on the carriageway was limited by the angle of incident of the laser beam on the surface and the black colour of the asphalt, which influenced the backscatter of the laser light.

3.1 3D-point cloud registration

Five spheres with a diameter of 15 cm were used as reference targets for registration purposes of the 3D-point clouds. Before registering the 3D-point clouds, the spheres had to be modelled by fitting a sphere with known diameter into the 3D-point cloud according to the least-square method. Hence, the mean absolute error was 0.7 mm and the standard deviation 1.0 mm. These results are mean values for the five reference spheres in the four scans of different loadings. For the sphere targets made of Styrofoam with a diameter of 12 cm, the mean absolute error and the standard deviation correspond to the results for the reference spheres.

For the registration of the 3D-point clouds, all the 3D-point clouds were registered into the coordinate system of the initial scan. The registrations were performed with the software Cyclone by Leica Geosystems AG (http://www.leica-geosystems.com). The registration quality is specified by the mean absolute error and the RMS (Root Mean Square). The mean absolute errors for the three registrations were 0.6 mm (initial-P1), 0.6 mm (initial-P2), and 0.5 mm (initial-P3). Furthermore, the RMS was calculated to 0.6 mm for each of the three registrations.

3.2 Deformation analysis between different epochs

As mentioned above, the deformation analysis of the TLS data was performed both area-wide and discrete. The latter was performed by using the sphere targets on the object.

The area-wide deformation analysis required a filtering of the 3D-point clouds by eliminating outliers and undesired points. Furthermore, the scanning section to be analysed was restricted to a 10 m by 20 m area (Figure 6). The filtering of the 3D-point clouds was performed with the software Geomagic Studio by Geomagic Inc. (http://www.geomagic.com). Hence, the area of the road surface was filtered identically for each scan. Filter algorithms were run for an automatic detection of outliers, a reduction of the point spacing (40 mm) and a smoothing of the 3D-point cloud by a free form filter. The average distance, which the 3D-points were moved, was calculated to 1.6 mm (mean value of all four scans) and the standard deviation of the residuals to 1.3 mm (mean value of all four scans).

The deformation analysis was performed with the software Geomagic Qualify. The 3D-point clouds of the different loading situations were compared to the initial situation. The residuals were calculated as the shortest distances from the scan points to the initial surface which was modelled by triangulating the 3D-point cloud.

In Figure 6, the residuals of the scan points of the loading situation P2 to the initial situation are shown. Deflections of the outer side of the cantilever slabs are detectable. The maximum deflection is around 20 mm. The results for the comparison between initial situation and loading situation P1 are similar but the sizes of the residuals are smaller. The influence of the different loadings on the resulting deflections can be clearly distinguished.

Table 1 summarises the results of the comparison between the different loading situations and the initial situation. Differences between the results of the different loading situations are clearly detectable. However, the maximum positive and negative residuals have to be looked at with care due to the fact that these values can be influenced by outliers which could not be detected during the filtering process of the 3D-point clouds.

Besides the area-wide deformation analysis, a discrete deformation analysis was performed by the 13 sphere targets which were arranged around the loads on the cantilever slabs (cf. Section 2.5). The target sphere centre points for the different loading situations were compared with the initial situation. Figure 7 shows the vertical displacements (Δz). The largest residuals can be detected for the targets 104 and 204 which were located close to the loads on the outer side of the cantilever slabs. The mean values of the residuals are calculated to -0.2 mm for the differences between situation P1 and initial situation (standard deviation: 1.6 mm), -1.7 mm for P2 and initial (standard deviation: 2.7 mm), and 0.4 mm for P3 and initial (standard deviation: 0.5 mm).

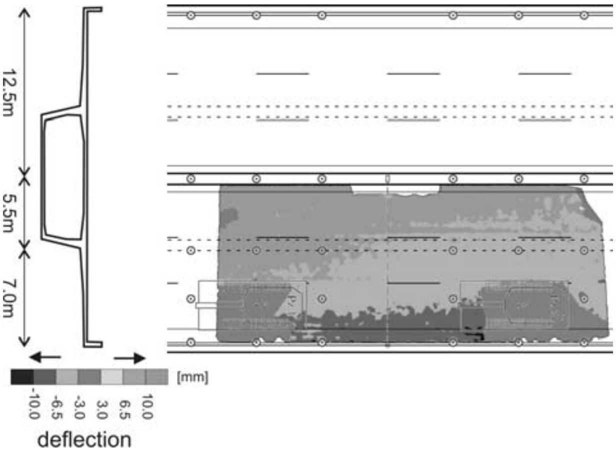

Figure 6. Deflections of cantilever slabs detected by terrestrial laser scanner (residuals of the scan points of loading P2 to the initial situation).

	Mean positive residual [mm]	Mean negative residual [mm]	Max. positive residual [mm]	Max. negative residual [mm]	Standard deviation [mm]
P1	0.6	1.4	6.0	10.5	1.4
P2	0.5	3.6	4.8	24.3	1.9
P3	0.5	0.9	7.6	9.6	0.9

Table 1. Mean residuals and standard deviations of the residuals for the different loading situations as a result of an area-wide deformation analysis.

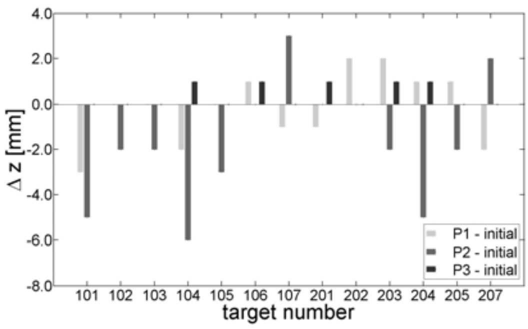

Figure 7. Vertical displacements of sphere centres between different loadings and initial situation measured by terrestrial laser scanner Imager 5006.

In general, it can be said that deformations of the cantilever slabs could be detected by the area-wide analysis as well as by the discrete analysis. The discrete analysis shows smaller residuals which are caused due to the fact that the target spheres could not be placed at the very outer side of the cantilever slabs. But it is difficult to compare the mean values of the target sphere residuals to the mean positive and mean negative residuals, which resulted from the deformation analysis by the software Geomagic Qualify, due to an unknown weighting of mean positive and mean negative residuals. However, it must be considered that the deformations detected by TLS only describe the deviation of the cantilever slab. Hence, the implementation of absolute vertical displacements is indispensable for the detection of settlement and tilting of the bridge girder.

4. COMPARISON OF TLS AND PRECISE LEVELLING

The load test on the Felsenau viaduct enabled the comparison of different geodetic measurement methods. Below, the results of the measurements by the precise levelling are summarised, and the results of TLS are compared with the results of the precise levelling.

4.1 Deformation measured by precise levelling

The reference height point close to the test field was determined for each loading situation by a precise levelling with 13 setups from a height transfer reference outside of the Felsenau viaduct. The accuracy for the reference height point was calculated to 0.36 mm (1σ). Furthermore, the height of the bolts in the test field was measured by a single observation due to efficiency reasons. The accuracy of the relative height determination for the bolts was calculated to 0.15 mm (1σ). The resulting accuracy of a single measurement of a bolt in the test field was computed to 0.50 mm (1σ).

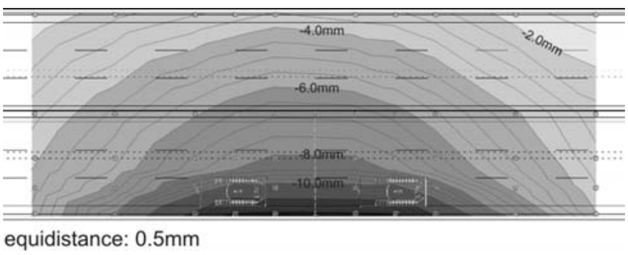

Figure 8. Deformations between initial situation and loading situation P2 of bridge girder detected by precise levelling.

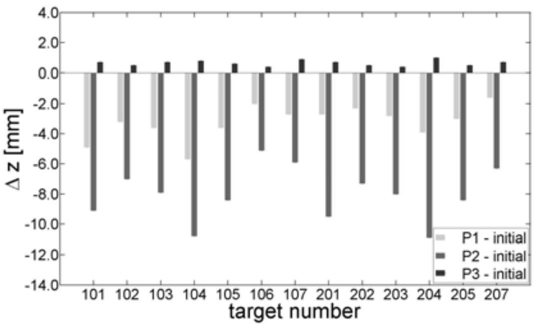

Figure 9. Vertical displacements of sphere centres between different loadings and initial situation measured by precise levelling.

Figure 8 shows the area-wide vertical displacement between the initial situation and the loading situation P2. Settlements and tilting of the bridge girder can be clearly detected. Furthermore, a deflection of the cantilever slabs is visible for the outer side of the slabs close to the loads.

For the precise levelling, the vertical displacements between the initial situation and the situations with different load conditions are listed in Figure 9. Hence, bolts 104 and 204 performed the largest deviations with 10.8 mm and 10.9 mm.

4.2 TLS versus precise levelling

The TLS data was recorded in a local system without any connection to the outside of the Felsenau viaduct. Hence, local deformations as the deflection of the cantilever slab were detected. In contrast to TLS, the precise levelling was connected to a transfer point outside of the Felsenau viaduct. Absolute deformations of the bridge girder could be detected.

For the comparison of TLS data with data of the precise levelling, a transformation of the TLS data into the precise levelling height system was required. At least, the settlement and tilting of the bridge girder had to be added to the TLS measurements. The additional vertical displacements of the reference targets of the terrestrial laser scanner were calculated by interpolating the vertical displacements of bolts for precise levelling which were installed close by. By analysing the vertical displacements of the TLS reference points, the settlement and tilting of the bridge girder could be determined under the assumption that the TLS reference targets remained stable to each other. Table 2 lists the calculated settlements and tilting of the bridge girder for the different loading situations.

	Settlement [mm]	Tilting [°]
P1	-0.85	0.0051
P2	-3.35	0.0111
P3	1.65	0.0040

Table 2. Settlement and tilting of the bridge girder for the corresponding load situations derived from the vertical displacements measured by precise levelling.

The vertical displacements between the different loading situations and the initial situation were transformed with the corresponding transformation parameters (Table 2). Figure 10 presents the transformed vertical displacements of the targets for TLS.

Figure 11 shows the differences between the transformed vertical displacements measured by the terrestrial laser scanner and measurements by the precise levelling for the targets in the test field. As a result, there are differences up to 3.5 mm. The displacements are normally distributed and no systematic deviation is detectable.

The mean residuals, respectively the mean vertical displacements, which were measured by precise levelling as well as TLS, are presented in Table 3. For TLS, the mean value refers to the transformed vertical displacements. The ranges of the mean values are similar for precise levelling and for TLS.

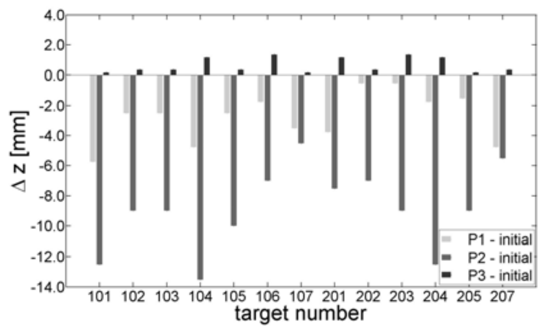

Figure 10. Transformed vertical displacements of sphere centres between different loadings and initial situation measured by terrestrial laser scanner.

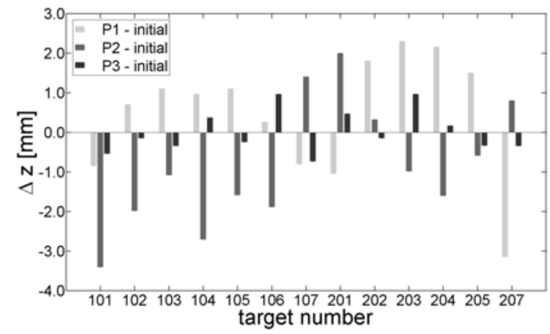

Figure 11. Differences between transformed vertical displacements of TLS and precise levelling for different loadings.

	Mean residual (initial-P1) [mm]	Mean residual (initial-P2) [mm]	Mean residual (initial-P3) [mm]
Precise levelling	-3.2	-8.1	0.7
TLS	-2.8	-8.9	0.7
Δ (TLS-levelling)	0.4	-0.8	0.0

Table 3. Mean residuals (vertical displacements) of deformation analysis for different load situations detected by precise levelling as well as TLS.

5. DISCUSSION

The results by TLS present relative deformations as deflections of the cantilever slabs (outer side) of up to 20 mm under a maximal load of about 100 tons. This deflection range could only be detected by the area-wide analysis whereas the target spheres performed relative deformations of up to 6 mm due to the more central target setup in relation to the bridge girder. For the detection of absolute deformations of the bridge girder, the transformations of the TLS data into the reference height system defined by precise levelling were required.

By comparing the transformed vertical displacements detected by TLS and the vertical displacements by precise levelling, the deformations of the bridge girder are within the same range. Maximum differences between the two measurement methods are around 3.5 mm. But considering the mean residuals for the different loading situations, the differences between TLS and precise levelling are less than 1.0 mm.

Generally, the Felsenau viaduct mainly performed deformations as settlement and tilting. The deflection of the cantilever slabs were minor compared to the other deformations.

6. CONCLUSIONS

TLS is a very fast acquisition method and does not require deployment of any targets on the object. Since the measurements are carried out touchlessly the performance and accuracy of the measurements depend on the surface properties of the object. For scanning road surfaces, black asphalt and small angles of incident influence the data quality. As for the Felsenau viaduct, the carriageway could be detected up to a range of about 20 m from the scanner station.

Regarding deformation monitoring on the Felsenau viaduct, TLS could replace the area-wide precise levelling. But, the transformation of TLS data into an absolute height reference system is essential for the detection of settlements and tilting of the bridge girder. Hence, for the connection to a height transfer reference outside of the viaduct precise levelling can not be omitted.

Our load tests on the Felsenau viaduct have shown the feasibility of deformation monitoring by TLS. A comparison with precise levelling allowed assessing the measurement accuracy and quality of TLS. In general, TLS is suitable for detecting deformations within the mm-range. But concerning applications at accuracy level such as the load tests on Felsenau viaduct, other measurement methods like precise levelling are indispensable. Therefore, TLS well complements traditional geodetic measurement methods but cannot replace them completely.

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