Comparative visualization of geometry of a hollow box girder using 3D-LiDAR – Part 1: Cross sectional area

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Abstract

With the mandatory introduction of the directive for recalculation of bridges in May 2011 in Germany, the administrations of the federal and state governments have a duty to demonstrate the stability of their bridge inventory. The requisite verification will be realized under consideration of the new increased traffic loads on the construction, in a four-step process. Particularly in older bridges the verification succeeds only using the computational resources of the original structural design. One option these reserves to be considered is the exact determination of the dead weight of the bridge. Since the existing as-built documents of the construction often digress significantly from the real dimensions, there are two options to resolve the issue. In addition to the technically very complicated and relatively expensive method of weighing the construction, the calculation can also be done indirectly through a combined process of photogrammetric measurement and non-destructive testing. On a practical case study will be demonstrated how the solution of this problem can succeed. For this is done in the first step to scan in detailed the inner topography of a part of the construction by a 3D laser scanner. The results of these tests are compared with the existing stock plans of the building. The aim of this study is to determine the dead weight of structure. Therefore, in the first part of this work sectional plans were extracted of the technical drawing and the point cloud to calculate the area of the interior. Based on the calculated areas in the sectional planes, the volume calculation should take place in the next step.

Introduction

In May 2011, was adopted in Germany a regulation according to which the owners of bridges are obliged to detect the stability of the constructions (Nachrechnungsrichtlinie [1]). This concerns the bridges that are owned by the federal or state governments. There are approximately 39.000 constructions. The reason for this regulation is that in recent decades the road traffic has increased significantly. In 1980 and 2010, for example, the gather subject to authorization of heavy goods traffic has increased by about a factor 15th [2]. Therefore, the bridges structure, recalculated under this procedure increased traffic loads.

To perform a classification of the urgency for the recalculation, a query was performed with regard to the evaluation scheme in an Information Management System. From this database, a total of around 2,400 constructions are identified which have the highest priority and are currently being recalculated. In the large part of this constructions, with the highest urgency is reinforced concrete structures, which are pretension. These were usually built in the 1950 and 1970th. At that time the constructions were built for a lifetime of at least 45 years (*Figure 1*).

Figure 1: „Age structure of the bridges on federal highways, with respect to the bridge area of the federal trunk road network in [%] "[3].

For each bridge construction are detected, the load-bearing capacity, the fitness for purpose and the fatigue. Be verification of sustainability is used in general a four-level calculation procedure. In the first two steps is use a default calculation method. If the verification of the safety of ultimate load cannot be used to establish, then further methods can be use, for example scientific methods in step four.

An important required parameter for the recalculation is the knowledge of the geometric dimensions of the construction. Normally, there are some as-built documents of the constructions from the construction phase. These can be used directly in the procedure of furnishing proof to step one and step two. In step three and step four of the recalculation, the exact knowledge of the geometric dimension of the bridge might be an important information. In this verification steps the calculations models are adapted to the actual circumstances. Furthermore, there are no as-built documents for some of the older bridges, so they have to be completely reconstructed [1].

The aim of the measurement is to calculate the dead load of the bridge element exactly. Is the dead load known, the partial safety factor of the original calculation can be mitigated and the actual weight can be determined. The liberated load bearing reserves of the construction can be scheduled for the increased traffic loads. The exact calculation of the dead load of a bridge construction is very costly. One possibility is, to weight the construction itself. For this purpose, it is necessary to install in the buttress areas hydraulic cylinders that raise the building. Afterwards the weight can be calculated from the required hydraulic pressure. This process technology is primarily suitable for smaller constructions. For bridges that are very long, and have a lot of buttresses, influence the adjacent field ranges the result strongly, so that the weight determination is inaccurate.

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Therefore, in this research the used procedure is a fundamentally different. Through a combination of innovative surveying technology with destructive testing methods of constructions, the weight of an element of a bridge is determined. In the final result, the dead lead of structure is calculated, including the respective measurement uncertainties of the different process technologies.

Construction and study of region

The bridge construction is the Köhlbrandbrücke in Hamburg (Germany). The construction was completed in 1974 after 4 years of construction. The Köhlbrandbrücke can be split into three sections. It consists of two ramp constructions and of the actual bridge construction. The bridge has a total length of 3,618 m and spans a billabong of the Elbe, the Köhlbrand. The ramps are designed as reinforced concrete construction. In the middle there is the highly visible cable-stayed bridge. At this the bridge is a steel construction (*Figure 2*).

Currently, various engineering offices are responsible with the recalculation of the construction. The investigations took place on the west ramp of the bridge. The western ramp consists of a total of 19 bridge fields with different spans. The spans are ranging a length of 42 m up to 70 m. In the plot, the western ramp has an S-shape after the cable-stayed bridge with a radius of 350 m. The bridge spans are a pre-stressed reinforced concrete construction, which was designed in the form of box girders.

The scanned hollow box girder is located between the support 107 and support 106 of the construction (*Figure 3*). The numbering of the supports here is taken from the existing as-completed drawing. The hollow box girder has a scheduled span of 70 m and is located in an average altitude of about 35 meters above the Köhlbrand. Due to the S-shaped form of the ramp, the hollow box girder has a special future in its longitudinal axis. The scanned hollow box girder represents the transition region from the straight part of the ramp to the arc-shaped part of the bridge. In order to maintain the dynamics of road traffic, this transition region is designed in the form of a clothoid. This means that the radius continually changes under consideration in each node along the axis of the hollow box girder until the final radius of 350 meters is reached.

Inside the hollow box girder, the thicknesses of the base plate and the bridges over the length of the hollow box are continually changing. In the middle the base plate has a planned thickness of 15 cm. Up to the supports the base plate reaches a thickness of 150 cm. In addition, the crosspieces and the ceiling show up to the supports a scheduled change in the thickness of the component. In the hollow box girder is also located on the crosspieces and on the ceiling various supply lines for the operation of the bridge (*Figure 8*).

Figure 2: Eastern view of Köhlbrandbrücke in Hamburg (Germany). In the foreground, the eastern ramp can be seen. In the background is the cable-stayed bridge with 135 m high steel beams [4].
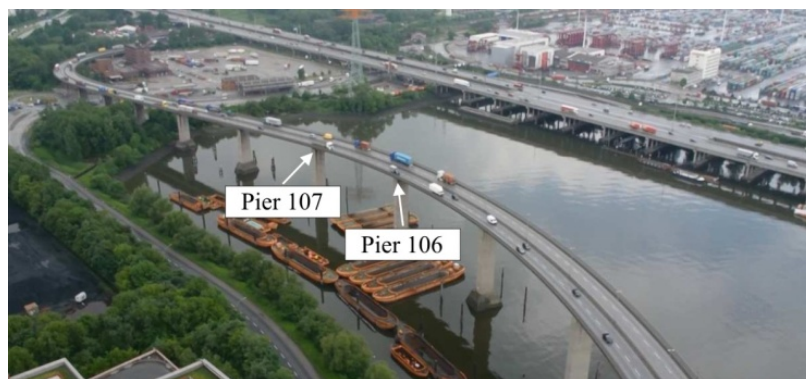

Figure 3: View on the western ramp of Köhlbrandbrücke. Between the support 107 and support 106 are the scanned hollow box girder [5].

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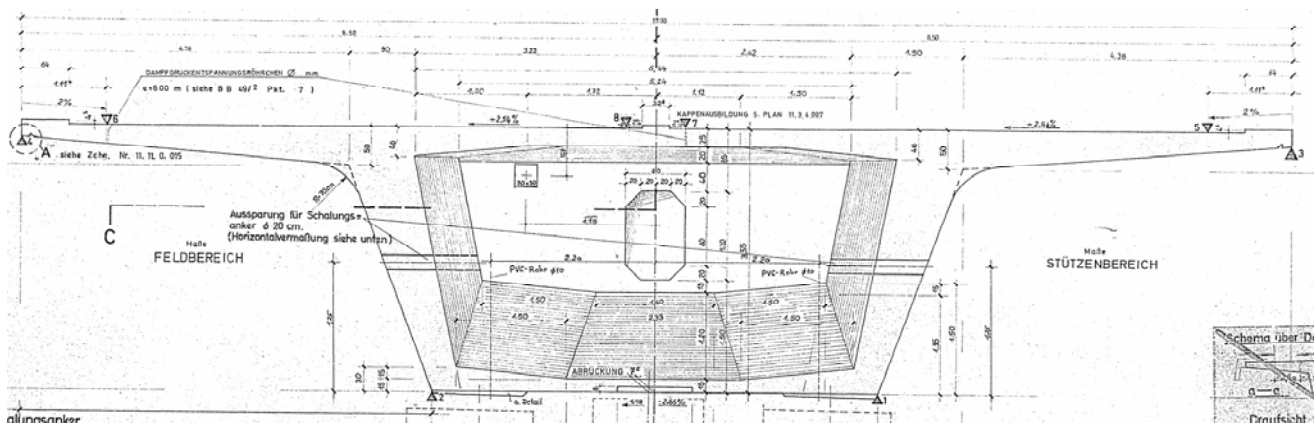
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Figure 4: Cross-sectional profile of the hollow box girder from the original as-built documents of the construction. The view is shown in the center of the hollow box girder towards to the support 107.

Presentation of a problem

For an exact determination of the dead load of the hollow box girder, in the first step the available volume must be determined as exactly as possible. Followed by the specific weight of the used material must be determined. From the determined volume and the specific weight, the weight of the hollow box girder can be calculated.

For the determination of the volume a number of steps are required. In the first step, the interior of the hollow box girder must to measure in a narrow measuring grid. Through the narrow measuring grid can be guaranteed, that the continually changing topography of the interior can be detected sufficiently and accurately (*Figure 4*). Furthermore, this is necessary for the subsequent measurements of the thicknesses of the component with the non-destructive testing out of the hollow box girder. The thickness of the component can be realized on this construction only on the use of non-destructive testing in connection with a commercially reasonable effort. Due to the height of the building, and the water present an outside measurement is almost impossible. Although mobile measurement systems have been purpose (e.g. drones) come into consideration, but these methods are not currently reached the required accuracy of the data collection [9, 10].

Also the determination of the geometric data of the hollow box girder with the classic process of measurement is very complicated. The hollow box girder changes over its length continuously the topography. Furthermore, in the technical drawing (*Figure 4*) the visible point-like transitions between the individual areas on the real building, are not recognizable. In particular, at the transitions of the crosspieces to the bottom plate, and on the base plate even these transitions are not recognizable (*Figure 8*). Therefore, it was decided to perform the measurement of the inner hollow box girder with a geographically scanned laser (LiDAR). Then the thickness of the component is determined with the ultrasonic-echo-method. In this way, it is possible to calculate the volume. The determination of the specific weight of the construction is the last step for the calculation of its own weight. This is done by sampling of core samples to determine the bulk density of the concrete and the use of the radar-method. With the radar-method, the reinforcement, which is located within the concrete construction, can be determined [11, 12]. From the concrete density and the reinforcement the specific weight is determined, which is required for calculation of its dead load.

In addition to the presentation of the technical possibilities of the process techniques to be checked simultaneously whether it is possible to calculation the dead load at a reasonable cost. The presented procedure provides a calculation in a first approximation. The overall result should be checked whether a gradual procedure in the determination of the dead load of structure is useful. So it is conceivable that an examination of individual real-sectional areas of the cross section already gives an indication of the result of the volume calculation.

Basic procedures

The scheduling of this study carried out in cooperation with the relevant procedures specialists and building owners. It was decided to carry out the measurements in total of four substeps:

1. Measurement with using a spatially sensed laser scanner (LiDAR). Creating a three-dimensional bridge-model with a CAD-Tool (Computer Aided Design) of the existing as-completed drawing. Detailed evaluation of the LIDAR measurements to the cross section profiles of the hollow box girder, where takes place the determination of the thickness using the non-destructive testing.
2. Calculation of the volume of the hollow box girder out of the point cloud with the LiDAR-method. Nominal-actual comparison with the scheduling documents. Determination of the uncertainty of measurement result by the data collection.
3. Determination the thickness of the component of the hollow box girder with the ultrasound-echo method. Extensive determination of the existing reinforcement with the radar-method. Sampling the hollow box girder by 18th core drilling. Determining the compressive strength and the bulk density of the concrete in standardized laboratory tests.
4. Development of an optimized measurement strategy for the determination the dead load of structure of the remaining hollow box girders of the western ramp, considering economic aspects.

In this article, the first section of the actual pending study will be presented. Represented are both results of the LiDAR-

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measurement, as well as considerations for an optimized evaluation in connection with the ultrasonic measurement.

Procedure of the study

Technical representation of the hollow box girder

In advance was created a technical drawing of the hollow box girder for the actual study with the LiDAR-system. The basis for this was the as-built drawings of the construction. The preparation of the technical drawing is required to be able to produce a geometric relation between the target data (as-built drawing) and the actual data (LiDAR point cloud measurements). The difficulty in the preparation of the technical drawing is in the geometric profile of the hollow box girder. Because the hollow box girder is located in the transition region from a straight line to a circular arc, it is corresponding to a profile of a clothoid. The geometric profile is very well seen in *Figure 5*. The general equations for the coordinates along a clothoid are:

$$X = \int_0^L \cos \frac{L^2}{2A^2} dL \tag{1}$$

$$Y = \int_0^L \sin \frac{L^2}{2A^2} dL \tag{2}$$

In the equations L describes the length of the clothoid and A is a constant parameter. For the hollow box girder between the support 107 and the support 106 this parameter is A = 175 m. In addition, for each point on the clothoid the corresponding centre of the associated must be determined to construct the relative inclination of the considered cross-section. Followed by it can be carried out the technical drawing of the hollow box girder.

Figure 6 shows the wire frame model with the sectional planes, in which the cross-sectional area of the interior of the hollow box girder changes. These cross-sections are highlighted by a white coloration line. In preparation for the measurements with

the ultrasonic and radar methods, the sectional planes of the study areas were also presented in a technical drawing (green colour). For each section plane was carried out the determination of the required coordinates with the equation (1) and (2). In total, the thickness of the component was determined at 27 different sectional planes. The sectional planes through the hollow boxes girder are shown in *Figure 6*. The aim was a uniform distance between the segmented planes of about 2.5 m. This was not always realized due to the existing supply lines.
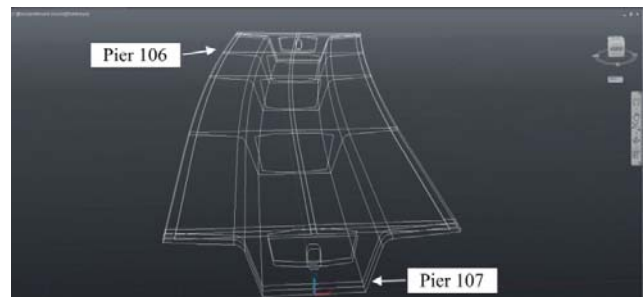
Figure 5: Wire-frame model, drawn from the as-built documents of the Köhlbrandbrücke. In the sectional planes are shown each changes in cross section.

After the various sectional planes have been generated, a three dimensional image of the hollow box girder was able to be created with the CAD-Tool. For this purpose, all reconstructed sectional planes were used as sampling points. *Figure 7* shows the automatically generated wire frame model. The interpolation was carried out hereby with a spline function. The extent to which this interpolation creates a sufficiently and accurate model-image of the hollow box girder, will be the subject of further studies.

For further explanations and the presentation of the results the sectional plane SP06 (*Figure 6*) is considered. The sectional plane is located at a distance of about 15 m to support 107.
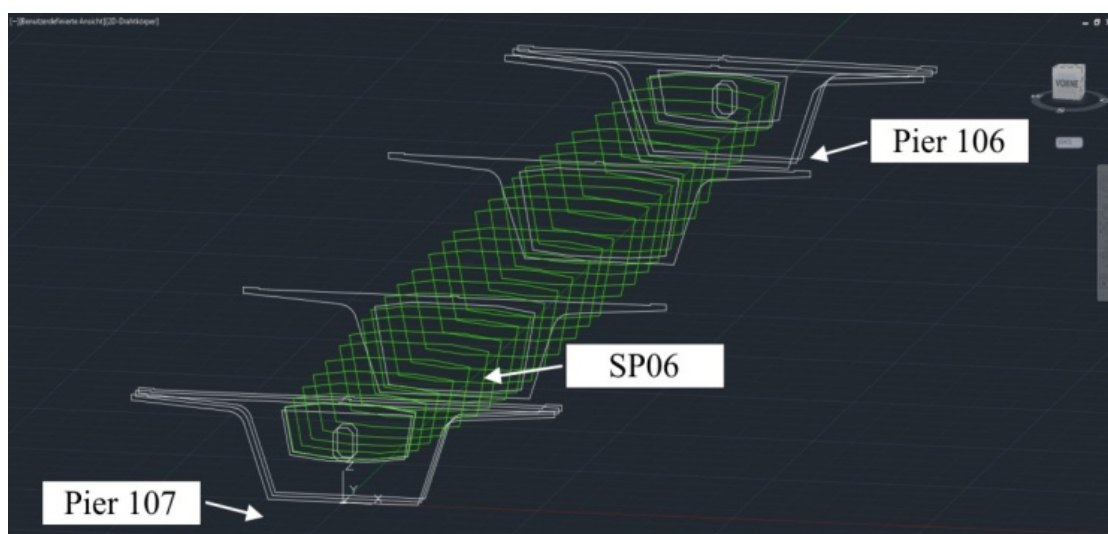
Figure 6: Sectional planes with non-destructive testing the component thicknesses were determined from the inside of the hollow box girder.
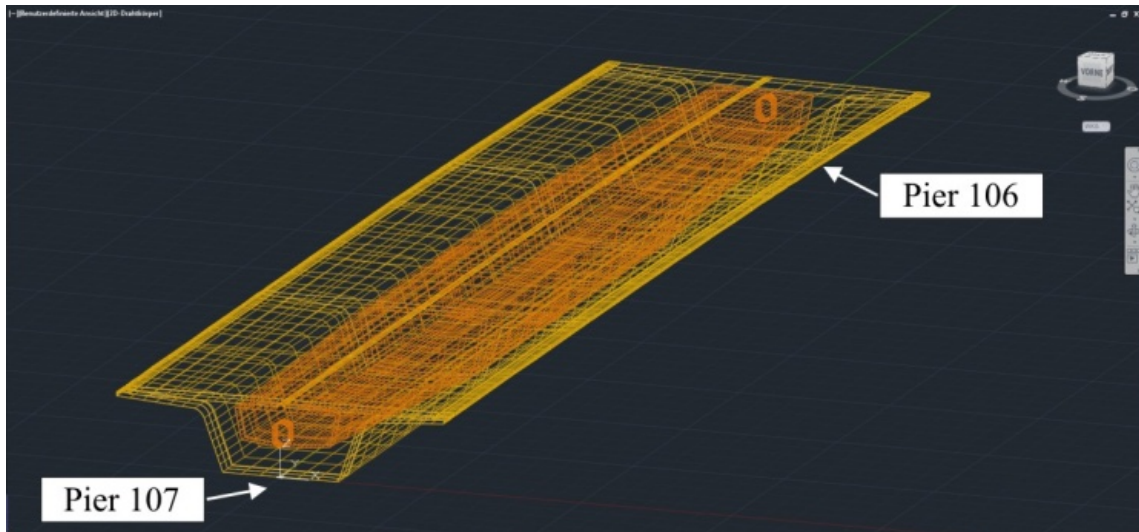
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Figure 7: A planar wire-frame model of the studied hollow box girder of the Köhlbrandbrücke.

LiDAR – Measurements

For the LiDAR-measurements it was used a commercially available measuring system. As part of the study five positions have been scheduled in the hollow box girder for creation a point cloud. The aim is to prove how many positions are required to get a sufficiently and accurate measurement result of the volume calculation. *Figure 8* shows the hollow box girder with a reference ball on the base plate (*Figure 8*). The reference ball has a diameter of 200 mm. Altogether five reference balls were placed in the hollow box girder. On the bulkhead frames of the supports are mounted in each case four square reflectors. Furthermore, at the left bar of the box girder it can be seen electric supply lines.

Figure 8: Sight in direction to the support 106 *from the middle of the hollow box girder. On the base plate is a reference sphere and on the bulkhead of the* support 106 *are besides to the transition square reference points.*

Figure 9 shows the implementation of the 3D-LiDAR-Scanner for a measurement. The measurement takes about 25 minutes for each measurement position. Altogether the measurements lasted about 3.5 hours including converting a re-set

up. In addition to the selective scanning of the hollow box girder, there was in parallel a photographic image capture by the scanner.

The produced point clouds were processed after completion of the measurements with the by the manufacture supplied software. From the collect data, a point cloud was created of about 157 million individual measurement points. After that, the calculated point cloud was inserted into the technical drawing in the CAD-Tool. As a reference point for inserting should be used the step-through-frame through the bulkhead (*Figure 8*).

Figure 9: Setting up the 3D-LiDAR-Scanner for measurement in the hollow box girder.

Here it was found that the point cloud has a significant deviation compared to the inventory documents, in their spatial orientation. The deviation is on the support 106 on average 100 mm, and on the support 107 on average 90 mm. *Figure 9* shows the offset in detail. Therefore, the step-through frame cannot

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use as a reference for the adaptation. To continue the study, the point cloud was manually fitted into the technical drawing. To this end, the point cloud may have to be raised both in the z-axis, as also be rotated by an angle. In this way, it could be achieved a positive result in terms of compliance. This will be the subject of further studies.

This was followed by a segmentation of the point cloud. The aim of segmentation is to cut off the areas in which the determination of the thickness of the hollow box girder is made with the ultrasonic method. For this purpose, a 100 mm wide segment is cut free from the point cloud of each sectional plane of the ultrasonic measurements. Thus, a total of 27 segments from the point cloud are extracted (*Figure 12*). The width of the sectional plane of 100 mm was chosen in order to obtain a sufficiently large number of measuring points for the reconstruction of the edges. It

is assumed that the geometric change of the cross section can be ignored in this area. Thereafter, it is determined the deviation quantitatively by comparing the technical drawing with the actually existing cross profile. For this purpose, in each case by a linear regression each edge component is reconstructed. The changes (topography) of the component surface are given in the form of a related standard deviation. By doing so, it is possible to relate the results of the thickness measurements on a straight line which in the first approximation is much easier. Followed by the cross-sectional area of the hollow box girder can be determined at each analysis area. About the summation can be determined conclusively, the volume of the hollow box girder. For the sectional plane SP06 (*Figure 6*) is shown below.
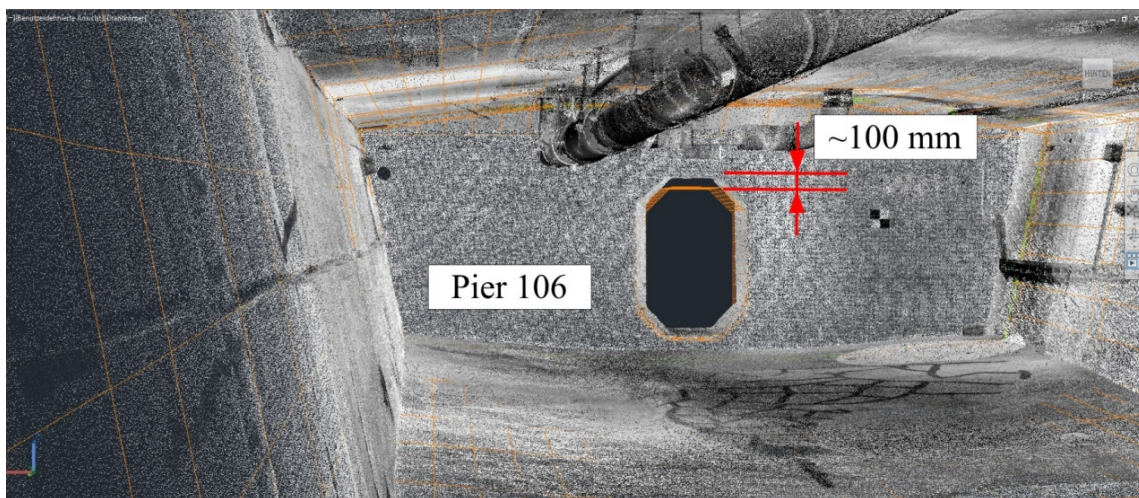

Figure 10: Detail of the offset of the point cloud from the step-through frame through the bulkhead at support 107 and support 106.
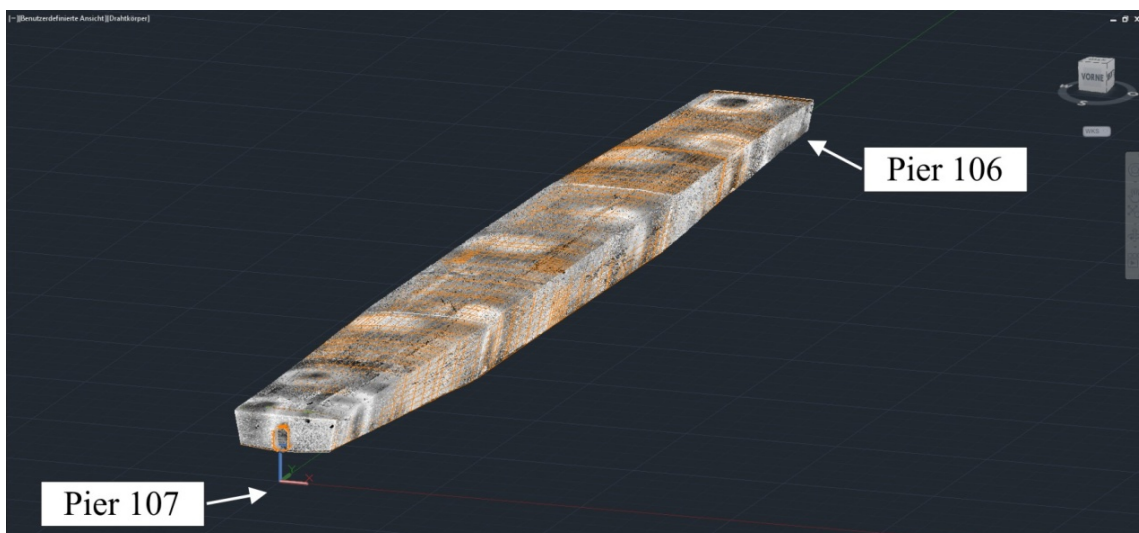

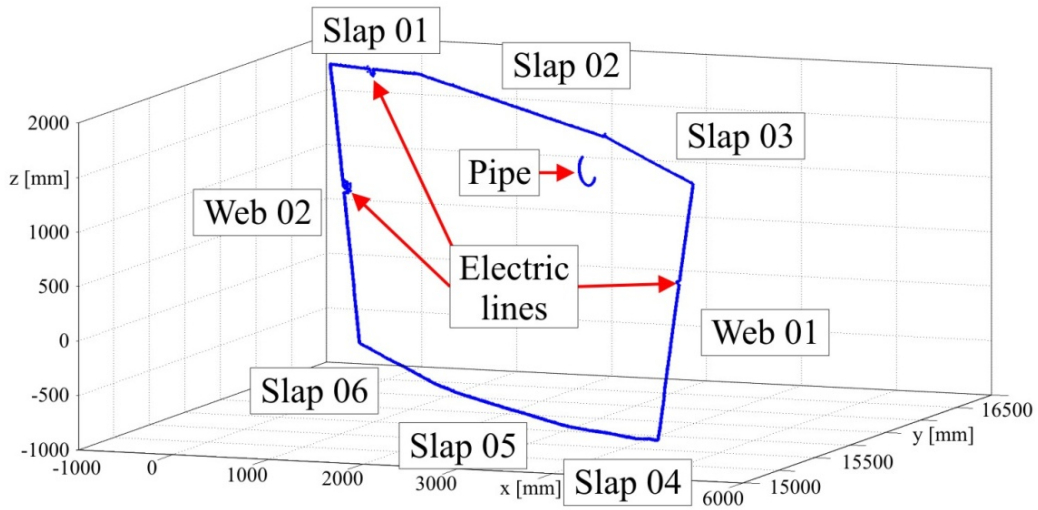*Figure 11: Manual fitted point cloud in the technical drawing of the bridge element.*

Figure 12: Segmented point cloud at the sectional plane SP06 (Figure 6) (blue line).

Figure 12 shows the segmented point cloud at the sectional plane SP06 (*Figure 6*). Beside to a total of 8 elements (Base and ceiling plate, web) are also visible the fixed supply lines which are on the wall of the hollow box girder. For further analysis, the data are processed with MatLab©. To calculate later the volume of the hollow box girder, in the first step the edges of the interior space will be reconstructed. In the second step is to calculate the individual area segments. With the thus calculated areas can be evaluated to a first approximation, the extent to which is differs with the target state from the actual state.

The calculation is performed, in which the total area is divided into 6 sub-areas (*Figure 13*). Each sub-area is calculated by specifying the respective deviation from an idealized face. These are calculated, by linear regression functions are determined along the area of the section. From the regression function and the measured values of point cloud a skill-based standard deviation is calculated. The hence determined standard deviation involves the measurement uncertainty of the scanner (manufacturer specifications: ±2 mm) as well as the deviation of the topography of the component surface. Thereafter the intersection points (red dot, *Figure 13*) of the sub-area are calculated from the regression functions.
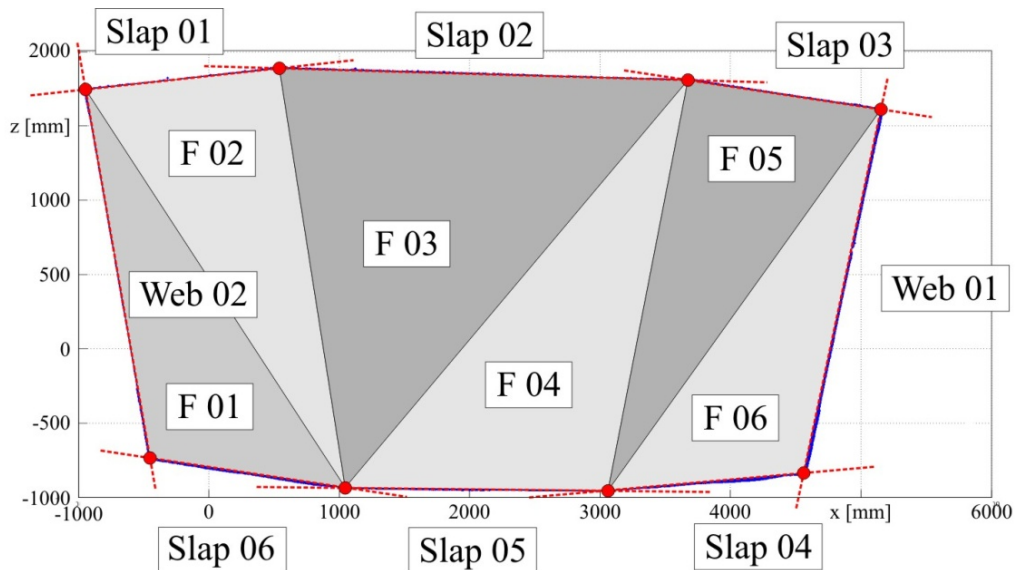

Figure 13: Technical drawing of the sectional plane (Figure 6) including the sub-area for the area calculation.

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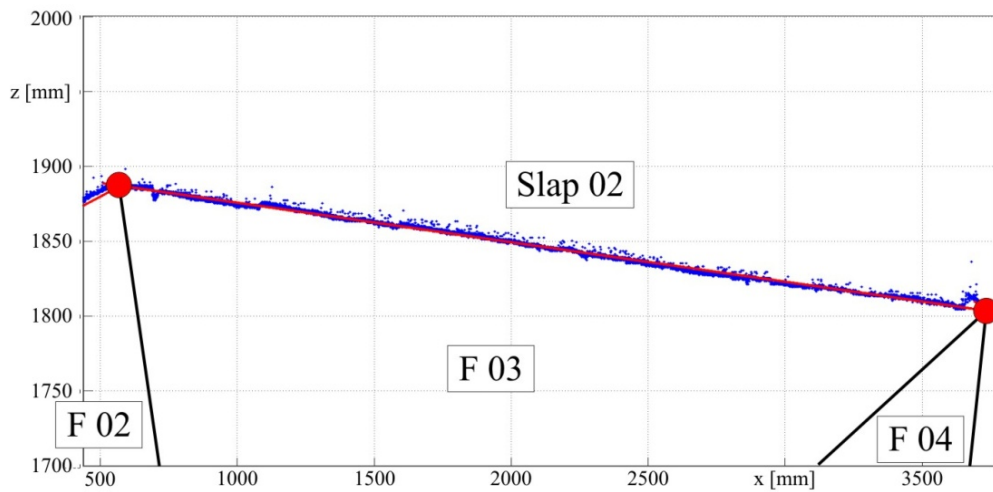
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Figure 14: Detailed view of the measurement results and regression function on the tarmac slab Slap 02 (blue dots - point cloud, red dots regression function) of the sectional plane SP06.

Figure 14 shows the detailed view of the evaluation for the upper middle area of the tarmac slab. The blue dots are the data points from the point cloud. Disturbing information such as the supply lines (*Figure 12*) were filtered out by all the points that deviate more than 50 mm from the mean are not considered. The red dots indicate the course of the linear regression function. The area of the point cloud which is taken into account for the calculation of the regression function has been set manually. The related standard deviation of the point cloud of the regression function is ±1,7 mm (SD$_{Slap02}$). Be considered in this case a total of 7983 data points of the point cloud. If the calculated related standard deviation compared with typical values for the determination of component thicknesses of concrete by non-destructive testing, it can be stated that the LiDAR measurements have a very high accuracy. The deviations in the thickness measurements of concrete can be ±10 cm due to the heterogeneity of the material. In a typical component thickness of 500 mm corresponds this to a deviation of ±50 mm.

For a first practical evaluation on the findings the sub-areas of the sectional plan are now calculated. In the calculation of the sub-area the related standard deviation is considered. The procedure is shown in *Figure 15* schematically for sub-area F 03. The mean area (FM) will be calculated with the help of the determinant calculation (Equation 3) using the determined intersection points. The mean surface F 03 is 4,445 m².
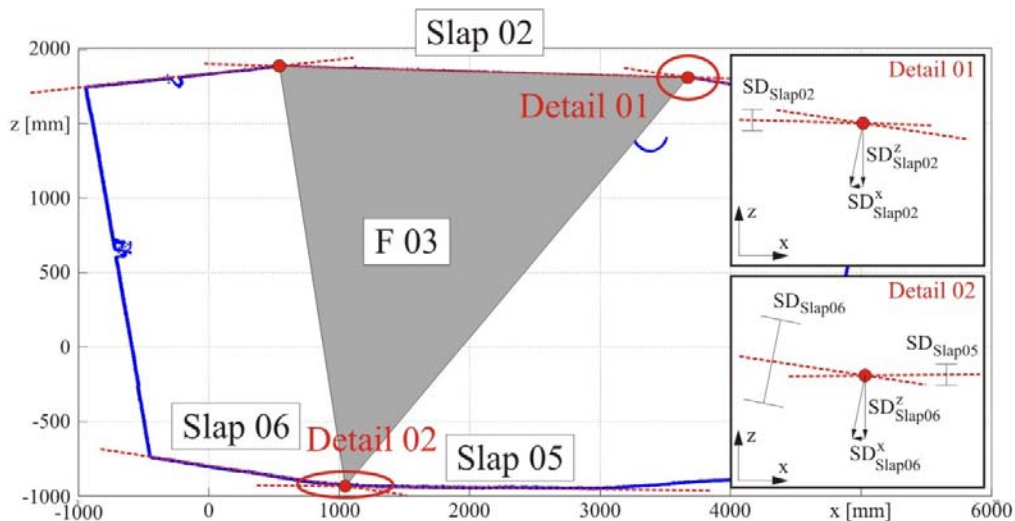

Figure 15: Schematic representation of the displacement of the nodal points for the calculation of the sub-areas of the sectional plane SP06.
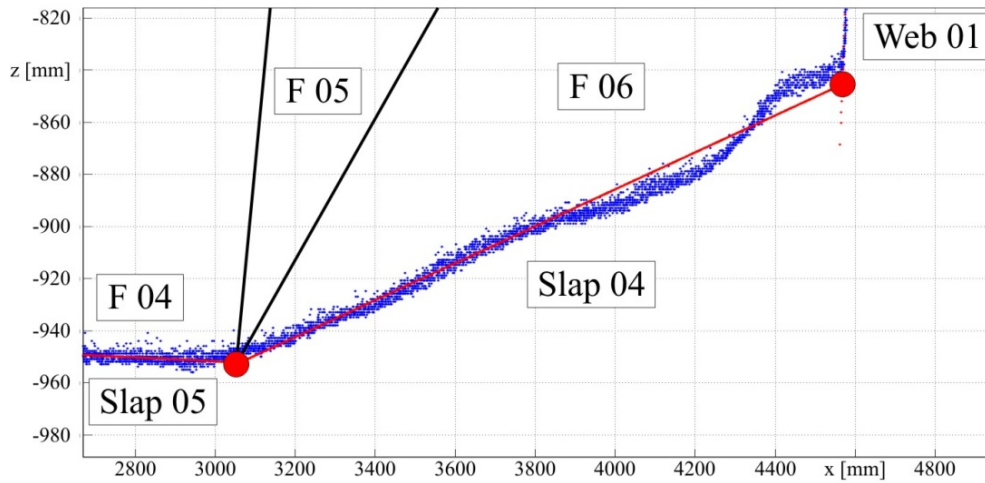
Figure 16: Detailed view of the measurement results and regression function of tarmac slab Slap 04 (blue dots - point cloud, red dots regression function) of the sectional plane SP06.

Followed by the deviations of the surface are determined with the help of the related standard deviation. For this purpose, the calculation of the displacement takes place of the three hubs (*Figure 15*). In the hub of Slap 02 to Slap 06, the worst case is assumed. That is the deviation with the largest displacement (SD_{Slap06}).

$$F_M = \frac{1}{2}\det\begin{Vmatrix} x_2 - x_1 & x_3 - x_1 \\ z_2 - z_1 & z_3 - z_1 \end{Vmatrix}$$

(3)

In *Figure 16*, the detailed view for the evaluation of the measured data for the section Slap 04 of the bottom plate. In contrast to the results on the tarmac slab Slap 02 can be clearly seen that here the topography of the component surface deviates significantly more from technical specifications (nominal value). Expressed as a related standard deviation, this deviation is calculated to ±4,8 mm (SD_{Slap04}). The adjacent sub-area F 06 of the sectional profiles is 1,844 m².

After evaluation of all measured data of the section area the total area was calculated as the sum of all partial surfaces. The results are shown in the following table. The calculated according to as-built documents for the interior surface of the hollow box is 15,037 m². Thus, the interior of the hollow box differs by about 2 %. The next step is to be determined by means of a model calculation the minimum and maximum deviation of the average total area using the deviations of the sub-areas.

The calculated interior space is in the sectional area in the middle by 2 % less than in the as-completed drawing of the specified construction dimensions. This leads to the assumption that the building overall is heavier than assumed in the calculation. Extent to which this is true, it can be determined only after the evaluation of all sectional planes and the thickness measurements of components with the non-destructive testing. The result of the study of the building may be heavier than in the original

calculation, does not necessarily have lead to a worse outcome in the verification. Case of the original calculation of the structure, the weight was subjected to a partial safety factor of 1,35 (γ). Is the weight of the construction now sufficient and accuracy know, this partial safety factor can be reduced in accordance with the standards on the value 1,2 (γ). This means, that the bridge in terms can carry 15 % more loads. Is the real weight now, as suggested above higher (in this case 2 %), remains in the sum a still compensable load reserve of 13 %. It can therefore be shown that because of this first approximate calculation of the areas an initial assessment can be done to the construction.

Calculated sub-area of the sectional plane SP06

Description	F_M [m²]	ΔF_{max} [m²]	ΔF_{min} [m²]
F 01	1.848	0,025	0,025
F 02	2,166	0,014	0,004
F 03	4,445	0,013	0,002
F 04	2,701	0,010	0,002
F 05	2,033	0,014	0,010
F 06	1,844	0,022	0,021
F_{SP06}	15,037	---	---

Summary

With this studies it is shown, that because of the assignment of a spatial working LiDAR-system, the inner topography of a

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hollow box girder of a reinforced concrete bridge can be detected very well. The measurements are made in the context of a real recalculation of a bridge construction. The aim of the study is in this case to calculate the dead load of the hollow box girder. It can be shown that the acquired measurement data have a very high accuracy.

Comparatively it takes less time for the actual recording of the measurement data. The effort for the post-processing of the results to concrete numerical values, under declaration of uncertainties, is whereas significantly higher. The available commercial software solutions are suitable limited for this purpose. In particular, the interfaces between the various suppliers are in this case, a major challenge. Therefore, it was decided to carry out the fundamental analysis with the software solution of MatLab$^©$.

Acknowledgment

References

[1] BMVBS: „Richtlinie zur Nachrechnung von Straßenbrücken im Bestand (Nachrechnungsrichtlinie)" *(„Standard for bridge re-analysis and assessment")*. Bundesministerium für Verkehr, Bau und Stadtentwicklung (BMVBS) (Federal Ministry of Transport and Digital Infrastructure), 2011, (German).

[2] Haveresch, K.: „Nachrechnen und Verstärken älterer Spannbetonbrücken" (*„Checking and Strengthening older Prestressed Concrete Bridges"*). Beton- und Stahlbetonbau 106 (2011), 2, S. 89–102, (German).

[3] BASt: "Brückenstatistik" (*"Statistics of bridges in Germany"*). Bundesanstalt für Straßenwesen (BASt) (Federal Highway Research Institute),
http://www.bast.de/DE/Statistik/Bruecken/Brueckenstatistik.html, 2015, (German).

[4] www.skyscrapercity.com, Postcount 172.

[5] www.pressebox.de, Pressemitteilung BoxID 639274, Kassel, Germany, 2013.

[6] Daniels, D. J.: "Ground penetrating radar. Institution of Electrical Engineers", London, 2004.

[7] Braml, T.; Taffe, A.; Feistkorn, S.; Wurzer, O.: Assessment of Existing Structures using Probabilistic Analysis Methods in Combination with Nondestructive Testing Methods. Structural Engineering International 23 (2013), 4, S. 376–385.

[8] Beutel, R.; Reinhardt, H.-W.; Grosse, C. U.; Glaubitt, A.; Krause, M.; Maierhofer, C.; Algernon, D.; Wiggenhauser, H.; Schickert, M.: "Comparative Performance Tests and Validation of NDT Methods for Concrete Testing". Journal of Nondestructive Evaluation 27 (2008), 1-3, S. 59–65.

[9] Uysal, M.; Toprak, A. S.; Polat, N.: "DEM generation with UAV Photogrammetry and accuracy analysis in Sahitler hill". Measurement 73 (2015), S. 539–543.

[10] Bulgakov, A.; Evgenov, A.; Weller, C.: "Automation of 3D Building Model Generation Using Quadrotor". Procedia Engineering 123 (2015), S. 101–109.

[11] Maierhofer, C.; Krause, M.; Mielentz, F.; Streicher, D.; Milmann, B.; Gardei, A.; Kohl, C.; Wiggenhauser, H.: "Complementary Application of Radar, Impact-Echo, and Ultrasonics for Testing Concrete Structures and Metallic Tendon Ducts". Transportation Research Record 1892 (2004), 1, S. 170–177.

[12] Wiggenhauser, H.; Kind, T.: "GPR Investigation of Reinforced-Concrete Structures: Radar for Bridge Condition and Performance Evaluations". Workshop, Washington, 2011.

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