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Laser scanning in diagnostics of geometric imperfections of hyperboloid cooling towers

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Summary

Hyperboloid cooling towers are distinctive tower structures designed to cool industrial waters by discharging their heat into the ambient air. Geometric imperfections of the hyperboloid cooling tower shell are the main, easily measurable symptom of structural strain and a significant factor in the development of safety hazards and failures of these thin-walled shell structures. This article presents an analysis of the use of a ToF and a phase laser scanner in the diagnosis of geometric imperfections of the reinforced concrete cooling tower shell. The reliability of TLS data in mapping the actual shape of the hyperboloid structure was confirmed on the basis of precise reflectorless tachymetry, which serves as reference data. Geometric imperfections of the hyperboloid cooling tower shell were determined by referring the TLS observation sets to a modified model hyperboloid, adjusted to the external surface by taking into account the actual, variable distribution of the shell thickness. Statistically confirmed compliance of the shell geometry analysis results, carried out on the basis of data obtained with two scanners with different parameters, showed no influence of the distance measurement system used in the scanning instrument on the effectiveness of detection of geometric imperfections of the hyperboloid structure. The results of the analyses of the shape of the cooling tower shell were consistent with the information on the geometric state of the structure, collected in the company archive. The imperfection maps generated on the basis of data obtained with the phase and the ToF pulse laser scanner clearly confirmed the deformations of the critical areas of the structure, which do not pose a real threat to the stability of the facility.

Keywords

terrestrial laser scanning (TLS) • ToF laser scanner • phase laser scanner • point cloud • deformation measurement • shell structures

1. Introduction

Hyperboloid cooling towers are distinctive tower structures that play a key role in industrial water cooling processes [Harte and Krätzig 2002]. The main structural element of these structures, which has the form of a hyperboloid shell, distinguishes cooling towers from other industrial structures not only by their geometrical shape, but also by the several hundred times lower thickness-to-dimension ratio of the structure [Bamu and Zingoni 2005, Asadzadeh and Alam 2014, Lingaraju et al. 2021]. Measurements of the geometry of the cooling tower shell are taken to determine its current position in the adopted reference system and to evaluate the geometric imperfections with respect to the model hyperboloid (designed or approximated) [Kocierz et al. 2018]. Geometric imperfections of the hyperboloidal shell caused by ongoing structural deformation, uncorrected manufacturing defects or inadequate reinforcement are a major, measurable symptom of structural strain and an important factor in the development of safety hazards and failures of these thin-walled structures [Gocał 1980, Wenjie et al. 2021]. The characteristic shape of the cooling tower shell, which determines the temporally varying deformations and displacements of the structure, dictates the programme, scope and timing of the measurement. In reliably determining the geometry of hyperboloidal cooling towers, the main difficulty arises from the dependence of the object's deformation on temporally variable factors, i.e. wind, ambient temperature or insolation [Zdanowicz 2011]. Minimising the impact of these phenomena determines the methodology for observing the structure sufficiently quickly to ensure that the measurement conditions are as constant as possible. On the other hand, the analyses of cooling tower disaster reports indicate the advisability of and the need to make the measurement more detailed and oriented towards the shape of the shell, especially its local variability [Gould and Kratzig 1999, Bamu and Zingoni 2005].

Several classical methods of measuring the shape of reinforced concrete cooling tower shells are established in surveying practice, i.e. the method of surrounding tangents [Kadaj 1973, Kasprzycki 1978, Jasińska and Preweda 2004], the method of spatial indentations [Gocał 1980, Shortis and Fraser 1991], or the photogrammetric method [Chisholm 1977, Majde 1991, Bernasik and Mikrut 2007]. However, since the implementation of precision reflectorless total stations into surveying practice, measurement systems based on the 3D polar method have dominated in the study of hyperboloid deformation of cooling towers [Woźniak 2011, Zdanowicz 2011, Gawałkiewicz 2011, Muszyński and Szczepański 2012, Kocierz et al. 2016, 2018, Głowacki 2022]. Nowadays, electronic industrial total stations, enable the determination of the distance to a non-reflective surface with an accuracy close to ±1 mm +1ppm, making the 3D polar method reliable and competitive in accuracy with systems using spatial forward indentation, while offering more favourable measurement economy [Kocierz 2014]. The measurement of the geometry of the cooling tower shell using the precision reflectorless total station technique is discrete in nature, comprising 400 - 600 points distributed uniformly over an interval of several metres in the form of a grid of meridional and latitudinal sections [Muszyński 2013, Kocierz et al. 2018].

A preferable alternative to the 3D polar method is the terrestrial laser scanning (TLS) technology, which provides, in a much shorter time, a multi-point data set (point clouds), transferring the actual shape of the cooling tower shell into digital form [Ioannidis et al. 2006, Muszyński 2013, Camp et al. 2013, Antoniszyn et al. 2016, Głowacki 2022]. With the operating speed of the laser scanner, it is possible to ensure constant observation conditions, minimising the impact of time-varying factors (which determine uncontrolled deformations of the object and limit the accuracy of the determined imperfections of the hyperboloid shell) [Makuch 2018]. The capabilities of terrestrial laser scanners, manifested in the remote and efficient acquisition of reliable high-resolution spatial data, have translated into numerous attempts to use these devices in the detection of geometric imperfections of cooling tower shells [Piot and Lançon 2012, Hojdys et al. 2012, Głowacki et al. 2016, Kocierz et al. 2018, Kwinta and Bac-Bronowicz 2021, Beshr et al. 2023]. References of TLS data to a defined in the design documentation or an approximated rotational hyperboloid are used to analyse shape changes and deviations from the design of thin-walled shell structures occurring during the erection (manufacturing defects) and operation of the cooling tower [Gawałkiewicz 2007, Głowacki and Muszyński 2018], as well as to confirm the correct construction of the facility [Bernardello and Borin 2022].

However, the multi-point collection of data acquired with a terrestrial laser scanner, which enables the detection of local deformations of the shell geometry, particularly important in strength analyses of structures, requires appropriate accuracy considerations [Gawałkiewicz 2007, Muszyński and Szczepański 2012]. It is crucial to select a laser scanner taking into account the used distance measurement system (pulse and phase), which determines the most important parameters of these devices and defines their practical implications [Fröhlich and Mettenleiter 2004]. An indispensable element of TLS measurements of a cooling tower is also a proper plan for the observation of the structure, with independent review of the measurement material. In order to reduce unintentional errors and to ensure the required accuracy of the measurement of a cooling tower with a terrestrial laser scanner, Kocierz et al. [2016] recommend that standardised measurements should be made each time, including an initial measurement of the structure by traditional methods with high accuracy, the results of which will form a grid for subsequent point cloud correlation. This paper analyses the use of pulsed and phase laser scanner in the diagnosis of geometric imperfections in the reinforced concrete shell of a hyperboloidal cooling tower and considers the need for standardised measurements, as postulated by Kocierz et al. [2016]. The effectiveness and precision of measuring instruments with different technical parameters were tested using the example of a cooling tower in service continuously for fifty years. The observation plan of the structure was supplemented by an independent review of the acquired measurement material on the basis of data acquired using the technique of precise reflectorless tacheometry.

2. Materials and methods

2.1. Research object

The test cooling tower is a structure located on the site of the historic Tadeusz Sendzimir Steelworks, built in the second half of the 20th century. In the design documentation, the reinforced concrete shell of this thin-walled structure had a shape of a rotating hyperboloid of variable thickness (0.4 m–0.12 m). The assumed geometry of the shell's central surface, which is a guarantee of the structure's stability, was given by the following parameters:

- height – 65.15 m,
- height to constriction – 51.55 m,
- radius at upper ring level – 13.52 m,
- radius at the constriction – 12.75 m,
- radius at lower ring level – 21.52 m.

The designed thickness of the thin-walled structure at the point of support on the columns is increased and is 0.4 m, then decreases to 0.3 m at the top edge of the bottom ring. Above this point, at a length of 10.90 m, the thickness of the shell changes linearly to 0.12 m; above this level it remains a constant value. The shell culminates in a reinforced concrete stiffening ring with a thickness (at the face of the wall) of 0.3 m and an external overhang of 0.7 m.

2.2. Terrestrial laser scanning

Terrestrial laser scanning of the cooling tower under study was performed with two instruments: a Riegl VZ-400 pulse scanner (commonly used in the study of such objects [Kocierz et al. 2016, Głowacki and Muszyński 2018, Kwinta and Bac-Bronowicz 2021]), and a Z+F Imager 5010 phase scanner (characterised by a higher measurement speed and accuracy of the position of a single cloud point). The basic parameters of both instruments are shown in Table 1.

Table 1. Technical details of laser scanners

Details	Riegl VZ-400	Z+F Imager 5010
Measuring procedure	pulse (or ToF, 'time of flight')	phase
Range [m]	max. 600	max. 187.3
Measurement rate [pkt/s]	max. 122 000	max. 1.016 million
Field of vision H/V [°]	360/100	360/320
Measurement accuracy	3 mm + 10 ppm	1 mm + 10 ppm
Measurement noise	no data	0.3–0.5 mm for every 10 m

The cooling tower was measured with the Riegl VZ-400 scanner (Fig. 1a) from four measuring stations, while the Z+F Imager 5010 scanner (Fig. 1b) from nine. The location of the scanning instrument stations was a result of the optimisation of TLS data acquisition for the entire structure shell, following from the industrial specificity of the object environment, the technical parameters of the scanners and the limited measurement time. Observations of the object were realised with reference to a stable observation network and the associated reference system. The adopted measurement methodology assumed tying scanners to unambiguously identifiable reference objects in the point cloud, i.e:

- 6" black and white Z+F Professional target plates, centred and leveled over the observation grid points;
- 150-mm-diameter steel reference spheres with customised adaptors (providing their consistent, stable position on the ground surface), distributed evenly around the test object and subjected to precision levelling (Fig. 1c).

a. b. c.

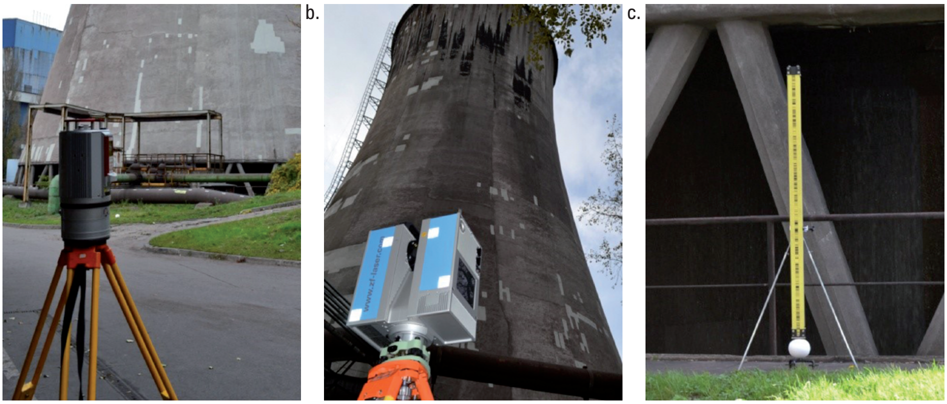

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Fig. 1. Terrestial laser scanning of the study object: a. Measurement with Riegl VZ-400; b. Measurement with Z+F Imager 5010; c. The reference sphere during precision levelling

2.3. Reflectorless tacheometric measurement

In order to verify the quality of TLS data, a reflectorless total station measurement was used, being a solution satisfactory in terms of accuracy, at the same time economical and possible to use under conditions of limited access to the object [Woźniak 2011, Muszyński and Szczepański 2012, Kocierz 2014]. The tacheometric measurement was performed with a Sokkia NET05 robotic total station, which guarantees precise measurements (angle measurement error – 0.5", distance measurement error in reflector measurement – 0.5 mm + 1 ppm, distance measurement error in non-reflector measurement – 1 mm + 1 ppm). To minimise the differentiating factors between total station and laser scanner acquired data, the measurement of each technique was performed at the same time. Due to the time rigour and the control that is the nature of the total station measurement, the observations of the cooling tower shell were made from four stations, evenly distributed around the structure and coinciding with the points of the observation network. The reliability of the measurement results was secured by carefully tying the stations to a minimum of three points of the observation network and by precisely determining the heights of the target axes of the instruments based on the three benchmarks located on the site.

Reflectorless tachymetric measurement of vertical profiles, formed from 30 points evenly spaced along the cross-section, representing the actual shape of the outer shell of the cooling tower, was carried out in a plane consistent with the bisector of the angle of incidence of the tangents. The location of the instrument stations in the plane of the defined cross-section ensured the alignment of the instrument's target axis and the axis normal to the shell to be measured, thus minimising the adverse effects of the non-perpendicularity of the incidence angle of the laser beam. In order to increase the accuracy of the reflectorless measurement, the distances to each point on the object were determined at least twice.

2.4. Registration and georeferencing of point clouds

The survey required combining (registering) the data acquired with the terrestrial laser scanner and georeferencing them by bringing the point clouds acquired with the pulse and phase laser scanner into a single, stable reference system. The several-step process of data registration and georeferencing was carried out in the Cyclone software. In the first step, the direct method [Mohamed and Wilkinson 2009] was used to estimate the transformation parameters. The point clouds were imported into a reference system, based on the known positions of the scanners and their references to target plates. The point clouds were then interconnected (indirect registration) based on the target plates and reference spheres uniformly distributed around the object [Becerik-Gerber et al. 2011]. In order to increase the quality of orientation in areas with no clearly identifiable targets and to improve the geometry of their layout, a cloud-to-cloud registration was used (assuming a static model of the structure), consisting of a search based on the Iterative Closest Point (ICP) algorithm [Besl and McKay 1992] for the best data match [Du et al. 2010]. The closed mesh principle was applied to exclude possible error propagation (each point cloud being a model, the subsequent alignment acted as data). In order to exclude possible error propagation, the closed mesh principle was applied (each point cloud being a model, in the subsequent alignment acted as data). The computational process also eliminated the negative impact of flawed links on the global orientation results by applying appropriate weighting (proportional to the accuracy of the targets, spheres or scan data) or excluding erroneous links.

2.5. Verification of the reliability of TLS data

Verification of the reliability of data obtained by terrestrial laser scanning technology, contingent on the class of the scanning instrument, the measurement optimisation methodology and the procedure of registration and georeferencing of point clouds, was based on the results of an independent reference measurement. In this respect, a precise reflectorless tacheometry (dominant in the practice of geodetic measurements of cooling towers [Wozniak 2011]) was used, competitive in terms of accuracy with systems using spatial forward indentation, while at the same time being more advantageous in terms of cost-efficiency of measurement. As a result of processing the total station acquired observation material in the WinKalk and GEONET software, the spatial coordinates of the reference points (forming four vertical profiles) located on the cooling tower shell and the corresponding mean errors were determined. Taking into account the erroneousness of the observation network points and control benchmarks, the mean position error of a point on the hyperboloid shell was 2.1 mm, and the maximum point position error did not exceed 2.9 mm.

By comparing the oriented point clouds with the results of the reference measurement, due to the specificity of laser scanning technology (replacing observations of single points with large data sets), the distances between the tachymetrically measured points and the planes fitted into the respective point cloud fragments were considered (Fig. 2). The accuracy of the determined discrepancies, which is the resultant of the accuracy of the total station data and the TLS observations, played a key role in the adopted verification procedure. The mean position error of a point in the reference measurement, including the errors of the points of the observation network and the control benchmarks, was assumed according to the mean error determined by the alignment (2.1 mm). The accuracy of the scanning data did not represent the classical concept of the mean position error of a single cloud point. The redundancy of TLS observations (which makes it possible to overcome the limited accuracy of the terrestrial laser scanner [Monserrat and Crosetto 2008]) provides much higher accuracies of the planes fitted into the point cloud, requiring the parameter σp (standard deviation) to be taken into account in this respect. In determining the accuracy of TLS data, the configuration of the measurement system (accuracy of the location of the scanner stations and reference points), defined by the mean position error of a point in the observation network (m_p = 0.5 mm) and the reliability of the registration and georeferencing process, defined by the mean orientation error (RMS), were also taken into account. The accuracy of the TLS data σ_{TLS}, understood as the length of the error vector with three components, was determined from the equation:

$$\sigma_{TLS} = \sqrt{m_p^2 + RMS^2 + \sigma_p^2} \tag{1}$$

The procedure for verifying TLS data was based on the distances (d_i) between the tachymetrically measured points and the planes fitted into the point cloud fragments. The approximation of planes with dimensions of 0.1 m × 0.1 m was performed using the least squares method, each time estimating the mean error of the fit (σ_p). The determined divergences were analysed within the limits of their variability, representing twice the mean error of their determination, which is the product of the mean errors of the reference measurement and the TLS data. A verification was also carried out for the set of divergences, determined for each measurement series, of their conformity to the normal distribution, as the expected error model, proving their randomness.

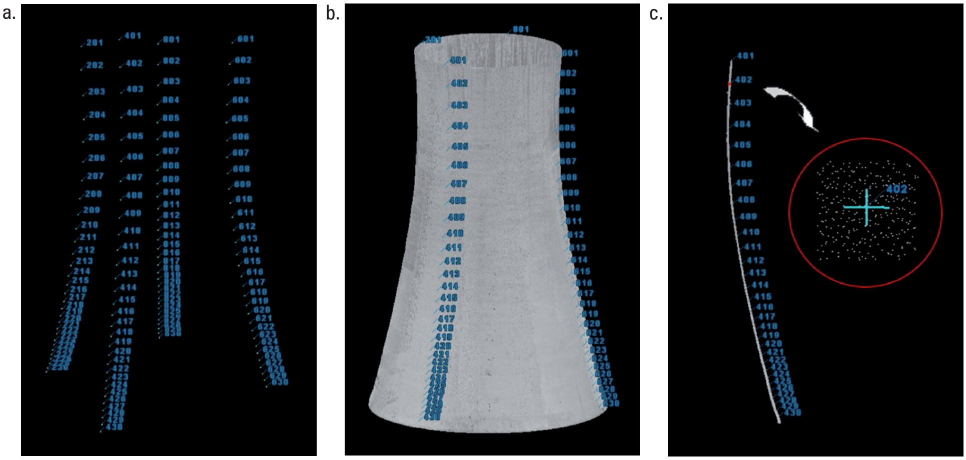

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Fig. 2. Verification of compatibility of TLS and total station data: a. reference points; b. initial compatibility check; c. verified point cloud fragments

The TLS data verification methodology used, using point cloud fragments of specified dimensions (0.1 m × 0.1 m), also formed the basis for the final data resolution analyses. The number of point groups (n) into which the planes were fitted was used to determine for each measurement series the density ratio (g), defining the average number of cloud points per 1 m^2 of surface and the average distance between adjacent points (known as spatial resolution, SR), derived from the relationship [Boulaassal et al. 2011]:

$$SR = \frac{1}{\sqrt{g}} \tag{2}$$

2.6. Determination of geometrical imperfections of a hyperboloid shell

In order to save computational power, the procedure for determining the shape deviations of the hyperboloid shell was preceded by a reduction of data redundancy, impeding efficient processing. The reduction in the number of point clouds was done using an *octree* structure, providing a recursive partitioning of the three-dimensional scene into smaller, regular fragments [Elseberg et al. 2013]. The volume of the TLS data was reduced by interpolating the point clouds to a regular distribution, corresponding to a point density of 0.02 m in the result sets (sufficient for analyses of geometric imperfections of the hyperboloid shell [Kocierz et al. 2018]). The algorithm used, sorting the cloud points based on their location into their respective cubes, for each determined the centre of gravity of the mass of the points contained therein, thus increasing (thanks to the redundancy of TLS observations) the limited accuracy of a single cloud point [Monserrat and Crosetto 2008]. Replacing the input point cloud with a set of gravity points was considered as a solution not only to the problem of reducing data abundance, but also to the issue of increasing the accuracy of a single cloud point (determined by averaging the observations).

A modified theoretical model of the structure, defined by the radius relative to height function, was used to determine the geometric imperfections of the reinforced concrete structure, representing the radial distances between the TLS observations and the theoretical shell [Mercik 2000, Malcher 1999]. The modified model was obtained by transforming the single-shell rotating hyperboloid model defined in the design assumptions (defining the central surface) into a theoretical model of the outer shell, which accounts for the actual varying shell thickness distribution. The comparison of point clouds acquired in successive measurement series with the structural model (defined by horizontal cross-sections in the form of heights and corresponding radial values) was carried out in the CloudCompare software with the qSRA (Surface of Revolution Analysis) overlay. The determined radial deformations of the shell (differences in measured and model radii) were assigned to each cloud point as a specific scalar field (SF) value, enabling hypsometric visualisation of the obtained results. The geometric imperfections of the reinforced concrete structure are presented in the form of two-dimensional maps, which are projections of a hyperboloid structure – that is undevelopable in the plane – onto the side of a truncated cone (considered to be a more appropriate way of presenting the distribution of deformation magnitudes of the entire surface of the hyperboloid shell than a cylindrical projection [Kwinta and Bac-Bronowicz 2021]). The parameters of the projection were chosen so that the axis of the cone coincides with the axis of the structure, while its radius satisfies the assumption of minimising the sum of squares of the distances from the cooling shell [Kwinta and Bac-Bronowicz 2021].

3. Results and discussion

3.1. Registration and georeferencing of point clouds

The registration and georeferencing of the data acquired with the two instruments was achieved using a hybrid method, reinforcing the unfavourable geometry of the measurement, being a combination of direct and indirect methods, performed on the basis of reference objects and the ICP algorithm. The synergistic combination of the different approaches to the registration and georeferencing process, allowed the advantages of each to be exploited and the disadvantages eliminated. The applied solution also attempted to automate the process as much as possible. The overall accuracy of the results of the multi-stage registration and georeferencing of the data was specified by the RMS parameter, which defines the quality of all the links used in the orientation. Defined as the mean orientation error, the RMS parameter for the registration of data acquired with the pulse scanner was 2 mm, while with the phase scanner it was

1 mm. The accuracy of the transformation process between the reference system and the global coordinate system of the registered point clouds was verified on the basis of the coordinates of the observation network points read from the point clouds. The average data compatibility for the pulse scanner was ±1 mm, for the phase scanner ±2 mm, with the maximum discrepancy for both instruments reaching ±2 mm in the horizontal plane and ±2 mm in the vertical plane.

The assessment of the quality and an independent control of the registration and georeferencing process of the data acquired with the pulse and phase laser scanner was also guaranteed by reference spheres with customised adapters, securing their invariable, stable position on the ground surface. The heights of the ten spheres, distributed evenly around the study site, were determined by close alignment of the elevations, determined with a precision leveller with reference to a benchmark located on the site. The aligned heights of the reference spheres (after taking into account their radii) gave the heights of the centres of gravity of the spheres, which constituted the quality control points, with an accuracy of no more than 0.0003 m. A check on the correctness of the registration and georeferencing was accomplished by verifying the correspondence between the heights of the centres of gravity of the spheres determined from the oriented TLS data (H_{TLS}) and those determined by strictly aligned precision levelling elevations (H_{NIW}). The obtained divergences ($\Delta H = H_{TLS} - H_{NIW}$) for the impulse instrument did not exceed the value of 0.002 m, while for the phase instrument they did not exceed 0.001 m, allowing a positive evaluation of the proposed multi-stage procedure for registration and georeferencing of point clouds. The small divergences in the orientation results of the point clouds acquired with the pulse and phase laser scanners (at the 1 mm level) were a consequence of the lower mutual coverage between the recorded clouds (due to the lower measurement speed of the pulse scanner, data from a smaller number of positions were acquired in the same real time), which limited the effectiveness of the ICP algorithm.

3.2. Verification of the reliability of TLS data

The reliability of the preprocessed point clouds acquired with the pulse and phase laser scanner was confirmed on the basis of independent total station measurements. By correlating the oriented TLS data with the results of the reference measurement, the considered distances were between 120 tacheometrically measured points (four cross-sections of the structure, created from evenly spaced 30 points) and the planes fitted into the corresponding sections of the point cloud. In the sets determined for each of the divergent instruments, all values were within the limits of conformity, being twice the average error of their determination (8.2 mm for the impulse scanner and 6.6 mm for the phase scanner, respectively). The determined divergences also did not exceed the limits of the desired accuracy of the description of the real shape of the hyperboloidal shell, which should represent 0.1 of its thickness at the constriction (a value of 12 mm). The parameters of the TLS data verification procedure are shown in Table 2.

Table 2. Parameters of the TLS data verification procedure

Determined parameters	Riegl VZ-400		Z+F Imager 5010	
	$\bar{x}$	x_{max}	$\bar{x}$	x_{max}
Mean error of planes fitting – σ_p [mm]	2.8	5.1	2.3	4.2
Accuracy of TLS data – σ_{TLS} [mm]	3.5	5.5	2.6	4.7
Accuracy of the determined divergences [mm]	4.1	5.9	3.3	5.3

For the two sets of divergences, verification of the conformity of their distribution was also done with the normal distribution as the expected error model, proving their randomness. The hypothesis on the normality of the divergence distributions was confirmed using the Shapiro-Wilk (S-W) statistical test at the five per cent significance level ($q = 0.05$). The obtained results of the W statistic (determined for the pulse scanner – 0.98801 and for the phase scanner – 0.98937) were values close to one, and test probability values ($p = 0.41 > 0.05$, $p = 0.48 > 0.05$) greater than the adopted significance level did not contradict the hypothesis of the normality of the divergence distributions (constituting a criterion for their randomness). The validity of the hypothesis of normality of the divergence distributions was also confirmed on the basis of probability – probability charts (Fig. 3), presenting the matches of empirical distributions to theoretical normal distributions (the so-called graphical test of normality). The graphs presenting the empirical distributions as a function of the theoretical distributions (straight lines) showed the approximate collinearity of the variables, confirming (by appropriate approximation of the theoretical distributions by the empirical distributions) the hypothesis of normality of the distribution of the determined divergences.

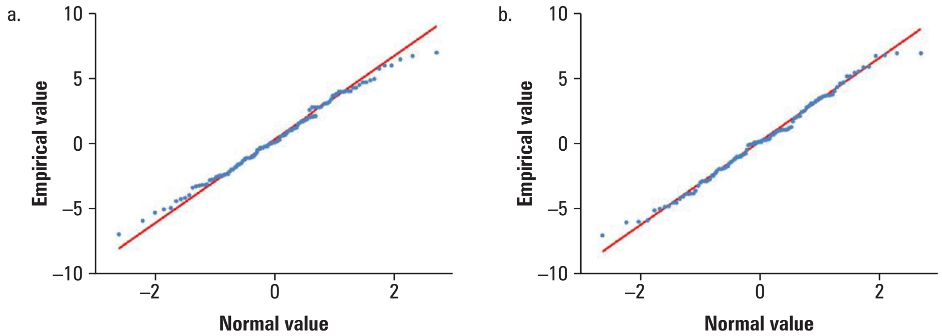

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Fig. 3. Probability – probability charts: a. Riegl VZ-400; b. Z+F Imager 5010

The final resolution of the pulsed and phase laser scanner data was also analysed based on the methodology for TLS data verification, using point cloud fragments of specified dimensions (0.1 m × 0.1 m). The mean values of the parameters determining the density (*g*), and resolution (SR) of the data, obtained by each instrument, are shown in Table 3.

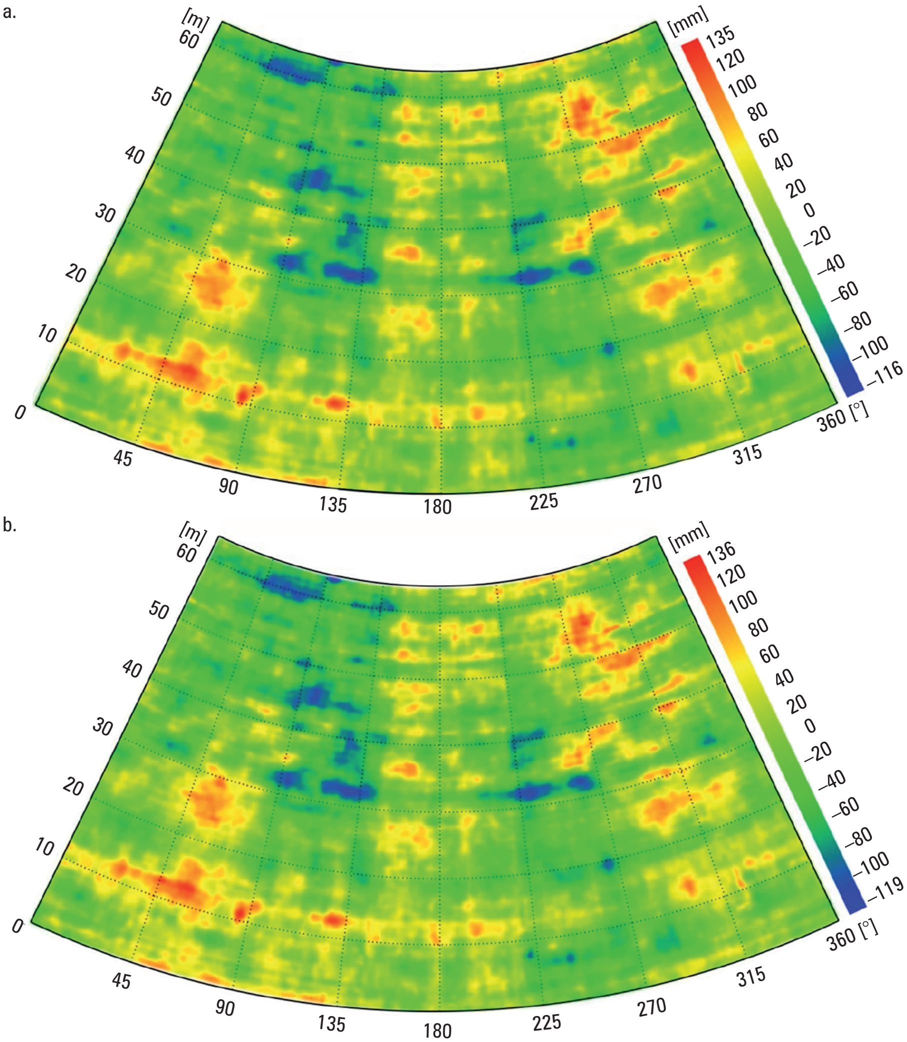
Table 3. Analysis of the final resolution of TLS data

Data resolution parameters	Riegl VZ-400	Z+F Imager 5010
Average density ratio – g [pts/m^2]	17588	341725
Average distance between cloud points – SR [m]	0.0075	0.0017

Satisfactory results of verification of the compatibility of point clouds (acquired with the pulse and phase laser scanner) and precise reflectorless tacheometry led to a positive assessment of both measurement instruments, as well as the applied methodology for acquiring and processing TLS data. The statistically confirmed normality of the divergence distribution showing the absence of systemic errors, also allowed the exclusion of the need to perform the standardised measurements postulated by Kocierz et al. [2016], reducing the errors in the TLS data by correlating the scans with the grid of points determined from the classical measurement. However, as can be seen from Table 2, the accuracy of point clouds acquired with a pulse scanner (commonly used in cooling tower imperfections studies [Kocierz et al. 2016, Głowacki and Muszyński 2018, Kwinta and Bac-Bronowicz 2021]) is lower compared to an instrument with a phase distance measurement system. In addition, the Z+F Imager 5010 scanner in the same real time allowed the acquisition of TLS data with more than 20 times higher final resolution (Table 3), predestining the detection of not only local deformations of the hyperboloid shell, but also surface damage (according to the methodology discussed in the works [Makuch 2018, Makuch and Gawronek 2020, Makuch 2023]).

3.3. Determination of geometrical imperfections of a hyperboloid shell

The geometric imperfections of the hyperboloid shell of the cooling tower were determined by relating the sets of observations acquired with the pulse and phase laser scanner (interpolated to regular distributions) to a modified model hyperboloid, adjusted to the external surface by taking into account the actual variable thickness distribution of the shell. The determined radial deformations, representing the differences between the measured and model radii, are presented as two-dimensional geometric imperfection maps of the reinforced concrete structure (Fig. 4). The imaging of the hyperboloidal shell of the cold storage that is not expandable on the plane was realised using the conical mapping, which allows for a clearer and more faithful representation of the object's surface than the commonly used cylindrical mapping [Kwinta and Bac-Bronowicz 2021].



Source: Author's own study

Fig. 4. Imperfections maps: a. Riegl VZ-400 pulse scanner; b. Z+F Imager 5010 phase scanner

The compatibility of the imperfection distributions shown in the maps (Fig. 4), determined from the data acquired with the two scanning instruments, was confirmed on the basis of histograms with the density curves of the Weibull distributions (Fig. 5). Statements of the homogeneity of imperfections determined from data acquired with the pulsed and phase laser scanner, based on a comparison of maps (Fig. 4) and the shape of the density curves of the Weibull distributions (Fig. 5), were supplemented by statistical analysis. The limited computational power, preventing inference from all the observations, meant that analyses were performed for less numerous subsets – samples. Sample populations reflecting geometric imperfections (so that inference about the geometry of the structure would be true) were established according to the criterion of spatial density of observations, specifying the minimum number of observations as a grid of 20 points along the meridians and 25 points along the parallels [Mercik and Borkowy 1999]. A sample of 1,000 imperfections (500 each for the instrument), located at the nodes of the single-dimensional grids (20 × 25), was used for the analyses. In order to assess the homogeneity of the results of the two measurements of the test object's geometric imperfections, the significance of the observed differences between each pair of imperfections (determined from the TLS data acquired with the pulse and phase laser scanner) was tested using the t-test for dependent groups. The hypothesis of homogeneity of the two sets of geometric imperfections was verified at the five per cent significance level (q = 0.05), assuming the normality of the distribution of differences between pairs of measurements (confirmed by the Shapiro-Wilk test). The calculated value of the t-test statistic was 0.5547. The resulting test probability value, higher than the adopted significance level (p = 0.63 > 0.05), did not contradict the null hypothesis, indicating the absence of statistically significant differences between the imperfection sets that were derived from the processing of point clouds acquired with the pulsed and phase laser scanner.

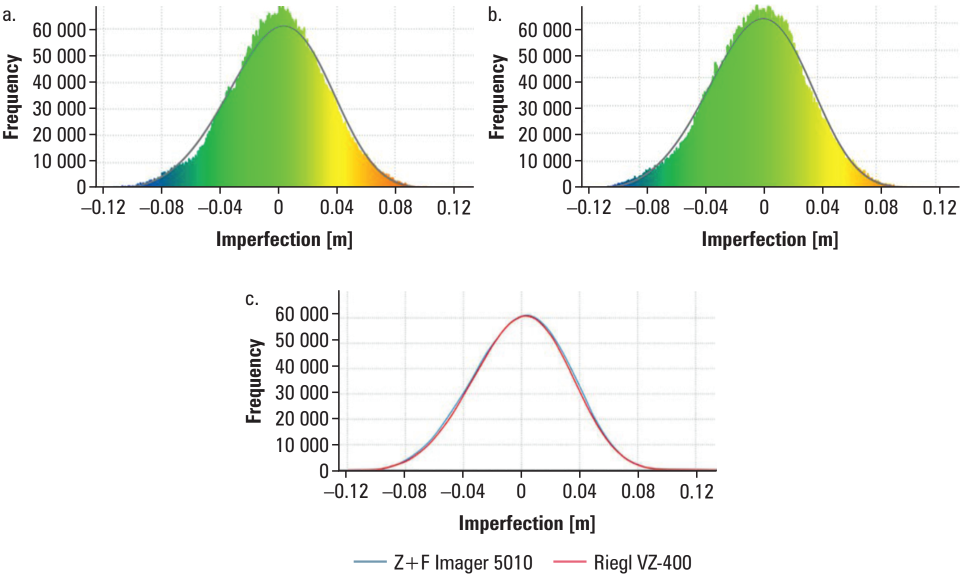


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Fig. 5. Histograms of imperfections with density curves of Weibull distributions: a. Riegl VZ-400; b. Z+F Imager 5010; c. comparison of curves

Consistent for both measuring instruments, the results of the analyses of the shape of the hyperboloid shell were compared with the information on the geometrical state of the structure collected in the plant archive. As the archive documentation indicates, the test cooling tower, constructed as a rotating hyperboloid in floating formwork, has a persistent flaw from the construction period – local execution imperfections between work cycles. The shape deviation maps generated on the basis of phase and impulse laser scanner data (Fig. 4) clearly confirmed deformations in the critical areas of the structure (especially between the first and second working cycles), ranging from –0.119 m to +0.136 m. The determined imperfection values, which are within the limits of permissible shell shape deviations, do not pose a real threat to the stability of the structure at present. However, in the prospect of further safe operation of the structure, it is necessary to carry out periodic measurements, which will exclude the progressive deformation of the hyperboloid shell.

4. Conclusions

Verification of the suitability of terrestrial laser scanning (TLS) for diagnosing geometric imperfections in the reinforced concrete shell of a hyperboloidal cooling tower was conducted using an operational structure at an industrial site in Poland as a case study. The empirical studies focused on assessing the quality of TLS data obtained using a pulsed and phase laser scanner and on verifying the consistency of the resulting analyses. The statistically confirmed compatibility between point clouds acquired by the two laser scanners and precise reflectorless tacheometry, used as reference data, validated the proposed methodology for TLS data acquisition, registration, and georeferencing, eliminating the need for additional standardisation procedures. The speed of measurement and the detailed description of the object's geometry are undeniable advantages of terrestrial laser scanning compared to traditional tacheometric surveys. Scanning the object with two instruments of different specifications provided reliable, quasi-continuous point sets describing the actual shape of the cooling tower shell, enabling equally effective detection and mapping of geometric imperfections in the hyperboloidal structure. However, it should be noted that the phase scanner, in the same real-time measurement period, delivered data with over twenty times higher final resolution. This allowed for a comprehensive diagnosis of the cooling tower shell's condition, revealing all deformations, losses, damages, and other surface irregularities.

The statistically confirmed compatibility of the geometric analysis results for the reinforced concrete shell, based on data obtained from pulsed and phase laser scanners, demonstrated that the measurement system used in the scanning instrument (which determines the key parameters of these devices and their practical implications) does not affect the effectiveness of detecting geometric imperfections in hyperboloidal structures. However, this raises the question of whether differences in results might become apparent when analysing objects with larger geometric dimensions (particularly systematic errors in phase scanners when measurements are conducted beyond their maximum range). Given the undeniable disparity between the dimensions of the studied object and those of modern hyperboloidal structures (e.g., the cooling tower of the Jaworzno Power Plant: 181.5 m in height; the cooling tower of the Kozienice Power

Plant: 185 m in height), addressing this question will be a priority in future research. Another proposed research topic for subsequent publications involves case studies evaluating the accuracy and efficiency of the latest models of terrestrial laser scanners that combine high-speed and long-range measurement capabilities.

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