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The potential of the terrestrial laser scanning for geometrical building facades inspection

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Summary. The long term success of any building facade maintenance program is directly influenced by the information available about the condition of facade structures. The objective of this paper is to find the potential of the terrestrial laser scanning technique to detect the deterioration on the surfaces of the building facades and to quantitatively measure the dimensions of the damaged areas. This paper is focusing on detecting the bowing of marble cladding and the surface delamination of brick facades. Field measurements were carried out using a terrestrial laser scanner. Measurements of the bowing of the marble panels were also carried out manually with a so-called “bow–meter”. According to the results of the manual measurements and the visual inspection, the bowing of the marble panels was calculated by fitting a second order curve to the laser scanning point cloud data from the centre line of the panel both in the vertical and the horizontal direction. The surface delamination of bricks and the weathering of joints can also be detected using the laser scanning system. The results show that the terrestrial laser scanning technique gives a reasonable method for measuring the bowing of marble panels and the delamination of brick building facades.

Key words: Laser scanning, Deterioration, Inspection, Marble panels, Building Facades

Introduction

The use of stone panels as cladding materials for facades has increased considerably in the last decades. Durability problems of marble claddings focus on the deterioration feature known as the bowing behaviour. [1] Masonry deterioration may start from small cracks in some of the individual bricks, and then progress through cycles of thermal movement alone, or in combination with freezing and thawing cycles, into wider cracks over a larger area. The most common masonry facade deteriorations are cracking, spalling, bowing (bulges vertically), sweeping (bulges horizontally), leaning, and mortar deterioration.

The deterioration of the building facades is typically assessed by visual inspections and destructive and non-destructive tests. The manual inspections are expensive, produce a great number of overlapping data and are time consuming. It is clear that a faster, more objective survey would offer a desirable alternative to these condition surveys.

This paper presents the background of terrestrial 3-D laser scanning technique and its use in detecting the bowing of marble cladding of building facades and the surface delamination of brick facades.

Terrestrial 3-D laser scanners

The terrestrial (ground-based) 3D laser scanner is a recently developed instrument that uses advanced laser measurement technology capable of obtaining thousands of point measurements per second. 3D laser scanners use either the Time-of-Flight (TOF) measurement method or the phase-based measurement to obtain the target point distance, shown in Figure 1. The Time-of-Flight measurement technology is based upon the principle of sending out a laser pulse and observing the time taken for the pulse to reflect from an object and return to the instrument. The phase-based measurement technology measures the phase difference between the reflected beam and the transmitted amplitude modulated continuous wave laser beam. The 3D laser scanner is capable of measuring up to 50 000 distances per second. [2]

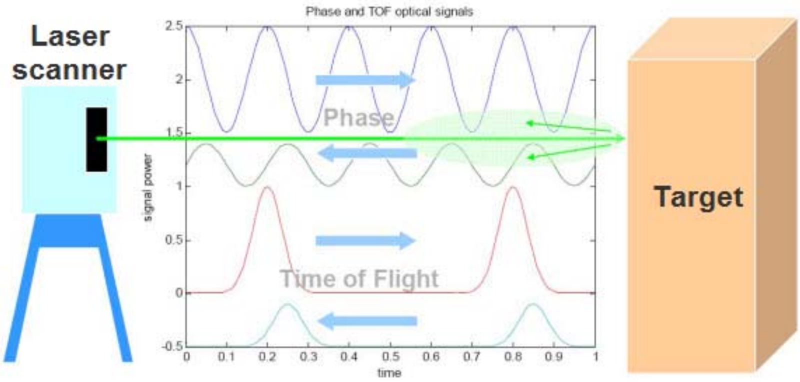

Figure 1. The operating principle of phase-based and time-of-flight 3D laser scanners. [2]

The output from the laser scanner for each point are one oblique distance ρ and two orthogonal angles θ and α, together with the additionally registered intensity of the returning signal distance. These spherical coordinates fully describe the three dimensional position of each point of the scan object in a local coordinate system relative to the scanner stand point. The geometric relation between these measurements and three-dimensional information of the scanned points could be calculated from equation 1. [3]

$$\begin{bmatrix} x_i \\ y_i \\ z_i \end{bmatrix} = \rho_i \begin{bmatrix} \sin\theta_i \sin\alpha_i \\ coc\theta_i \sin\alpha_i \\ \cos\alpha_i \end{bmatrix} \qquad (1)$$

where x, y and z are the point cloud coordinates; ρ_i is the slope distance between the laser scanner instrument and the object; θ_i is the horizontal angle at the scanner head; and α_i is the vertical angle at the scanner head.

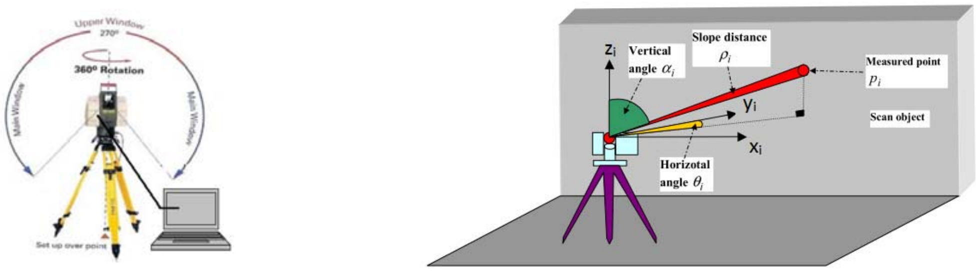

Figure 2. Spherical measuring system with a laser scanner system. [3]

The data received from laser scanning have been widely used in survey applications, global positioning, maintenance of historical sites and structural monitoring. The last two decades have seen the development of various scanning technologies and various defect inspection methods and algorithms have been developed using terrestrial laser scanning. [4]&[5]

Field measurements and data analysis

Field measurements using a terrestrial laser scanner were carried out on two facade walls at Helsinki University of Technology (TKK). A flow chart for the execution sequence of the terrestrial laser scanner technique is shown in Figure 3.

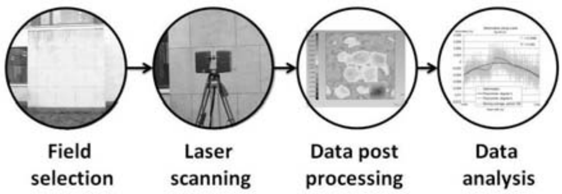

Figure 3. Flow chart of the laser scanning technique.

The field measurements were carried out with FARO LS 880HE80 terrestrial laser scanner and manually using bow-meter. The distance measurement of the terrestrial laser scanner is based on phase difference technique. The scanner was located about 5 m from the centre of the marble wall as shown in Figure 4 and 11 m from the masonry wall.

Figure 4. An overview of the scanned facades.

The FARO Scene software was used to filter noise and delete additional and unnecessary points from the point cloud. Geomagic Qualify and Realworks Survey software were used for further analyses of the data. For the purpose of a more in-depth analysis with other mathematical software, the coordinate system of the point cloud was transformed. The origin of the system was transferred to the lower left corner of the fitted plane of the facade. Likewise, the point cloud was thinned out in order to manage the measurement data better, resulting in 4, 5 and 7 mm grids to the data. Geomagic Qualify software was also used for further analyzing the magnitude of the deformation of the marble panels and masonry façade.

Measurements of the bowing of the marble panels were also carried out manually with a so-called “bow–meter”. The “bow–meter”, shown in Figure 5a, is a 1400 mm straight bar with a digital calliper which allows the distance from the edge of the bar to the panel surface to be measured accurately. The bowing of the marble panel was measured in the vertical and the horizontal direction as shown in Figure 5b.

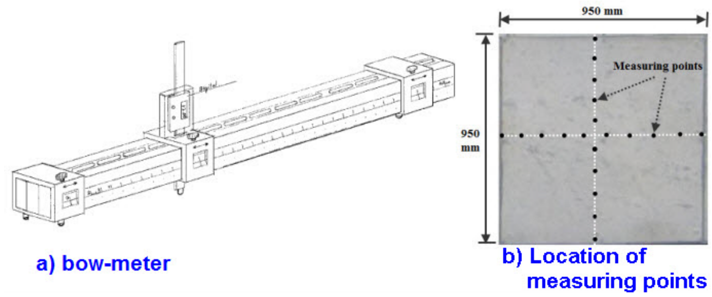

Figure 5. Manual measurement of the bowing of marble panels.

The bowing of marble panels was calculated by fitting a polynomial curve to the laser scanning point cloud data in the vertical and horizontal directions.

Calculation of the bowing of marble panels

Deterioration of marble panels involves several parameters and properties. Shape deformation is the most obvious phenomenon, where the panels bow either convexly or concavely out of their original plane. In addition to the bowing there also appears some permanent volume changes i.e., the marble expands. [6] The bowing magnitude of marble panels was calculated using equation 2.

$$B = \left(\frac{d}{L}\right) * 1000 \qquad (2)$$

where B is the bowing magnitude expressed in (mm/m); d is the measured value of bowing in (mm); and L is the measuring distance between the supports of the marble panel in (mm).

According to the results of the manual measurements and the visual inspection, the bowing of the marble panels was calculated by fitting a second order curve to the laser scanning point cloud data from the centre line of the panel both in the vertical and the horizontal direction. The polynomial equations of the vertical and horizontal bowing are shown in Table 1.

Table 1. The polynomial equations of the vertical and horizontal bowing.

	Vertical bowing	Horizontal bowing
Polynomial equation	$f(z) = a_2 * z^2 + a_1 * z + a_0$	$f(x) = b_2 * x^2 + b_1 * x + b_0$
Coefficients	$\begin{pmatrix} 1 & z_1 & z_1^2 \\ \dots & .. & \dots \\ 1 & z_n & z_n^2 \end{pmatrix} \begin{pmatrix} a_0 \\ a_1 \\ a_2 \end{pmatrix} = \begin{pmatrix} y_1 \\ \dots \\ y_n \end{pmatrix}$	$\begin{pmatrix} 1 & x_1 & x_1^2 \\ \dots & .. & \dots \\ 1 & x_n & x_n^2 \end{pmatrix} \begin{pmatrix} b_0 \\ b_1 \\ b_2 \end{pmatrix} = \begin{pmatrix} y_1 \\ \dots \\ y_n \end{pmatrix}$
	z is a variable of the panel height	x is a variable of the panel width
	$y_1 \dots y_n$ are the bowing values	$y_1 \dots y_n$ are the bowing values

The horizontal and vertical bowing of marble panels were calculated using mathematical equations which describe the curve fitting of the terrestrial laser scanning point cloud data. The following example shows how to calculate the horizontal bowing magnitude of the centre line of the marble panel. The bowing magnitude of the vertical centre line of the marble panel is calculated using a similar calculation.

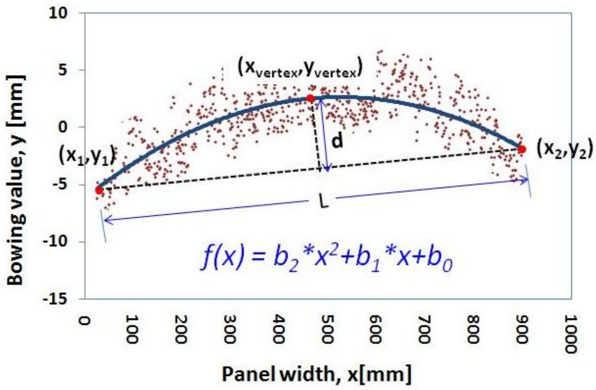

Figure 6. Example of the polynomial curve fitting of the point cloud data.

As shown in Figure 6, the value of the measuring distance between the supports of the marble panel in (mm) was calculated with equation 3.

$$L = \sqrt{(y_2 - y_1)^2 + (x_2 - x_1)^2} \tag{3}$$

where (x_1,y_1) and (x_2,y_2) are the first point and the last point of the fitted polynomial curve respectively.

The maximum bowing value of the marble panel was measured from the vertex of the quadratic polynomial curve. The coordinates of the vertex of the curve are:

$$x_{vertex} = \frac{-b_1}{2b_2} \tag{4}$$

$$y_{vertex} = f\left(\frac{-b_1}{2b_2}\right) = b_2 * \left(\frac{-b_1}{2b_2}\right)^2 + b_1 * \left(\frac{-b_1}{2b_2}\right) + b_0 = -\frac{b_1^2}{4b_2} + b_0 \tag{5}$$

The measured value of bowing of the marble panel in (mm) is calculated with equation 6.

$$d = \left(y_{vertex} - y_1 - \left(\frac{y_2 - y_1}{x_2 - x_1} * (x_{vertex} - x_1) \right) \right) * \left(\frac{(x_2 - x_1)}{\sqrt{(y_2 - y_1)^2 + (x_2 - x_1)^2}} \right) \tag{6}$$

The bowing magnitude of marble panels calculated with equation $B = \left(\frac{d}{L} \right) * 1000$, (mm/m).

Results and discussion

Bowing of marble panels

The field measurements of the marble panels show a remarkable convex bowing, as seen in Figure 7. The reference plane of the magnitude of the deformation of the panels is determined by the Geomagic Qualify software. One panel on the fourth row shows a clear concave bowing. One reason for the panel bowing could be water penetrating behind the marble panels, which increases and accelerates the deterioration of the panels. The failure of the lateral fixing of the panels could also be a reason for the marble panel bowing.

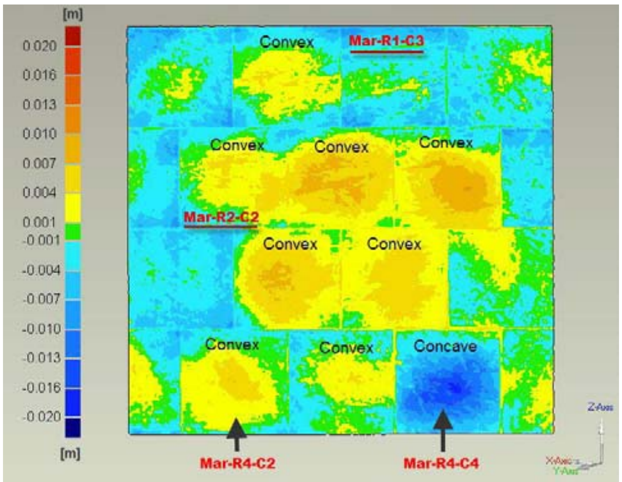

Figure 7. Terrestrial laser scanning data colouring by the magnitude of the deformation.

The results of the manual measurement of two marble panels using the bow-meter are shown in Figures 8 — 9. The values of the bowing of the panel “Mar-R4-C2” are 5.1 and 6.9 mm/m for the horizontal and the vertical directions respectively. The coefficient of determination (R-square) for the curve fitting of the manual measurements of the panel “Mar-R4-C2” is above 0.95.

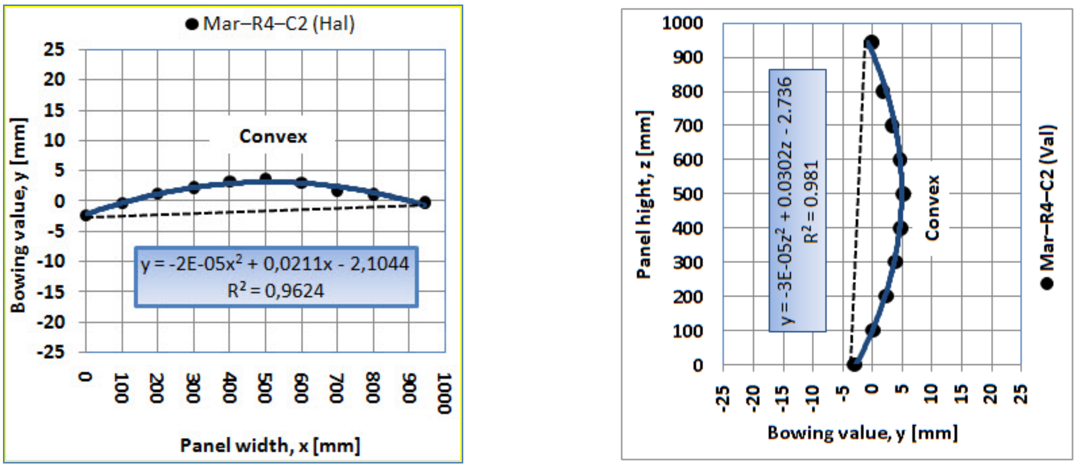

Figure 8. The manual measurements of the bowing of the marble panel Mar-R4-C2.

The values of the bowing of the panel “Mar-R4-C4” are -11.2 and -14.3 mm/m for the horizontal and the vertical directions respectively, which indicates a concave bowing of the panel in both directions. The coefficients of determination (R-square) for the curve fitting of the manual measurements of the panel “Mar-R4-C4” are 0.99 and 0.89 for the horizontal and the vertical directions respectively.

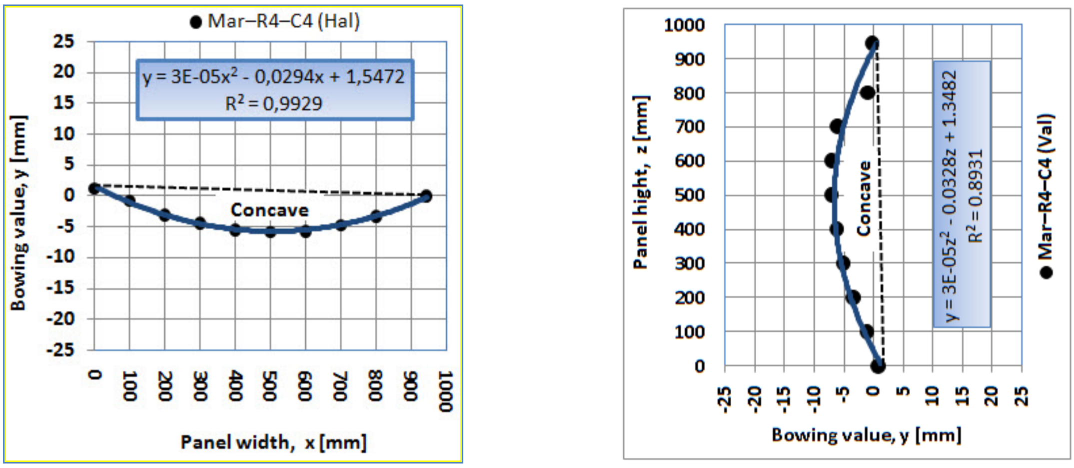

Figure 9. The manual measurements of the bowing of the marble panel Mar-R4-C4.

The results of the manual measurements and the visual inspection of the bowing of the marble panels show that the quadratic polynomial curve fitting was the best alternative for measuring the bowing magnitude using terrestrial laser scanning point cloud data.

Corresponding to the manual measurement, two examples of the bowing in the marble panels are shown in table 2 and figures 10 – 12. Figures 11 and 12 are shown laser scanning data strips with width of 2 mm across the panel in the horizontal and vertical directions. The maximum convex bowing magnitude was measured on the vertical direction of the panel “Mar-R4-C2”. The value of the bowing is 8.5 mm and the standard deviation of the distance of the measured laser scanning points from the fitting curve is 2.2 mm. The R-square coefficients of the curve fitting to the laser scanning point cloud data in the vertical and the horizontal direction are 0.6 and 0.4.

The concave bowing of the panel "Mar-R4-C4" is distinct in the visual inspection, the manual measurement and the curve fitting of the laser scanning point cloud data. The horizontal and vertical bowing values of the panel "Mar-R4-C4" are 11.2 mm and 14.3 mm respectively. The standard deviation of the distance of the measured laser scanning points from the fitting curve is 2.4 mm. The R-square coefficients of the curve fitting in the vertical and the horizontal directions are 0.76 and 0.82.

Table 2. The bowing magnitude of the marble panels using terrestrial laser scanning system.

Marble panel	Bowing direction	L	d	Standard deviation[1]	Type of bowing	Bowing magnitude
		(mm)	(mm)	(mm)		(mm/m)
Mar–R4–C2	Horizontal	915	5.3	2.2	Convex	6
	Vertical	940	8.5	2.2	Convex	9
Mar–R4–C4	Horizontal	920	-11.2	2.4	Concave	-12
	Vertical	925	-14.3	2.4	Concave	-15

[1]) Standard deviation of the distance of the measured laser scanning points from the fitting curve

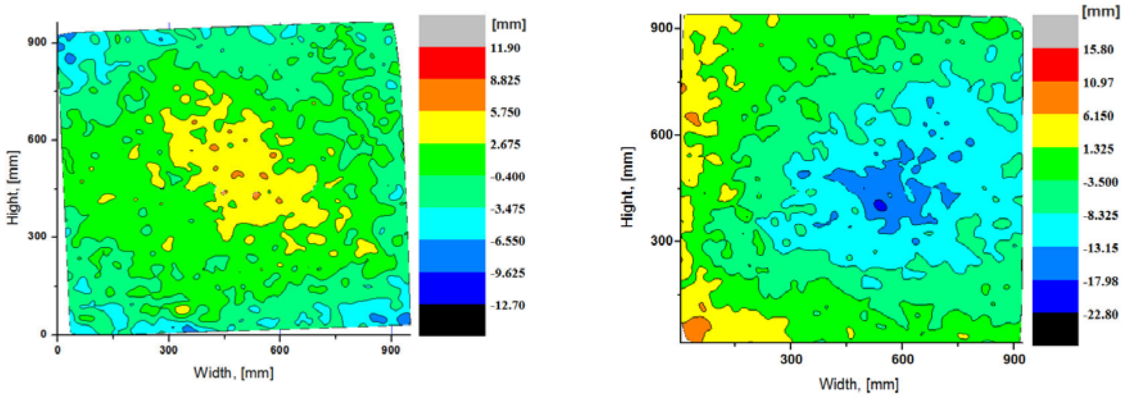

Figure 10. Terrestrial laser scanning data colouring by the magnitude of the bowing of the panel.

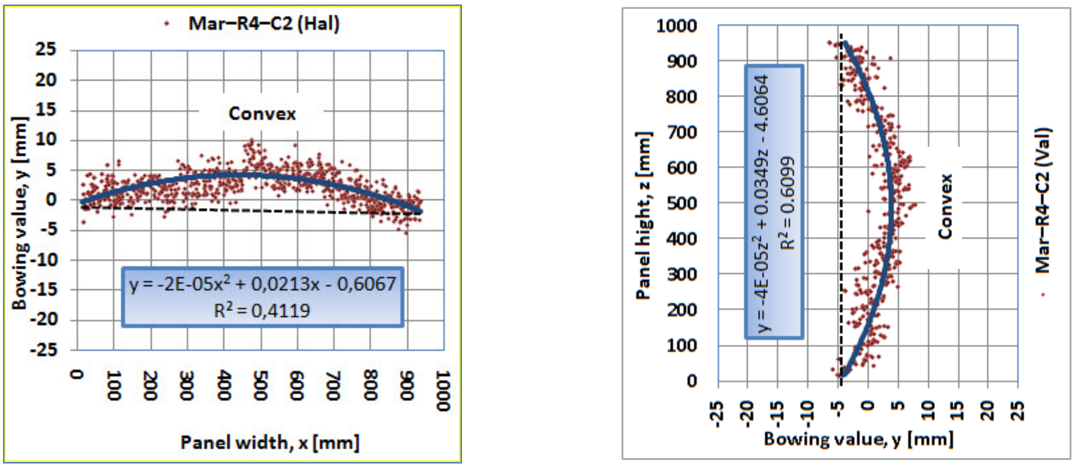

Figure 11. The horizontal and vertical bowing in marble panel Mar-R4-C2.

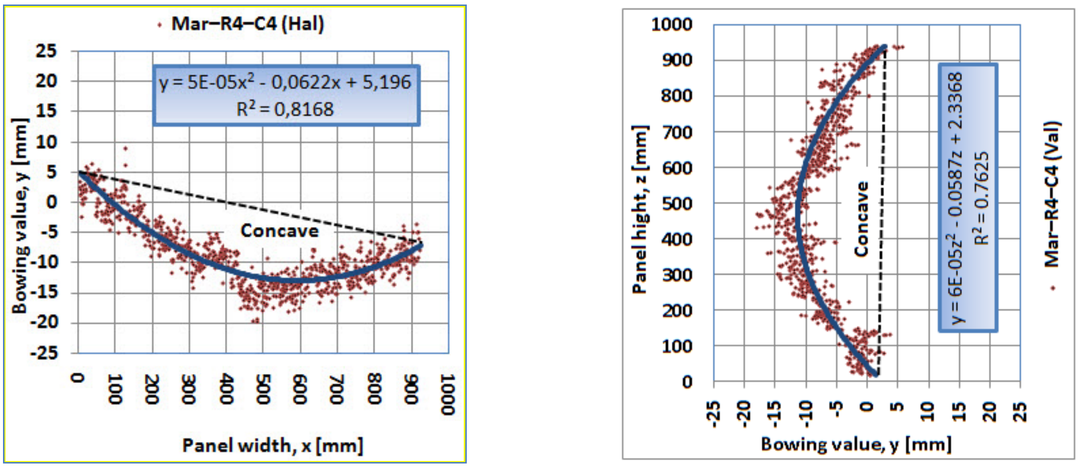

Figure 12. The horizontal and vertical bowing in marble panel Mar-R4-C2.

Surface delamination of bricks

The terrestrial laser scanning technique was used to determine the surface delamination of bricks. Figure 13 shows an example of the terrestrial laser scanning data for a masonry wall. The detected bulging of the bricks at some parts of the masonry wall was about 10 mm, which might be an indication of a wider delamination of the wall in the future. The detected depth of the weathered plaster of the joint is about 10 mm.

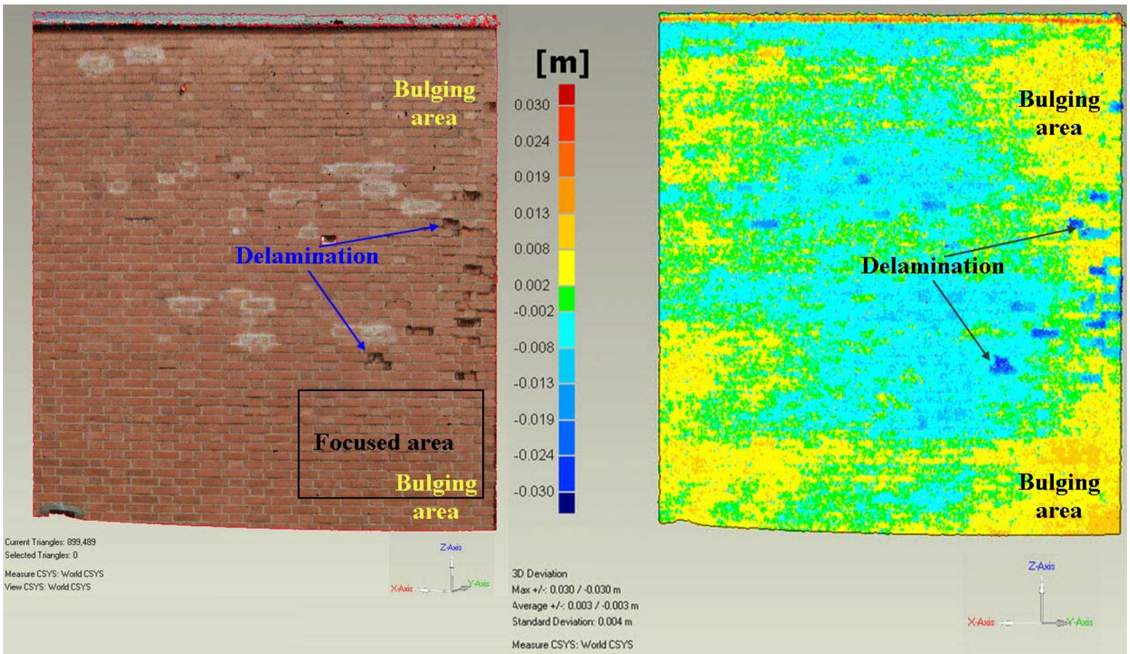

Figure 13. Delamination of bricks and the deterioration of joints detected from the laser scanning data.

For a more accurate analysis of the deterioration of the brick wall an area of about 1000 mm x 2000 mm is zoomed as shown in Figure 14. The maximum bulging f the bricks (redish colour) was about 10 mm from the outer surface. The depth of the weathered plaster of the joint (bluish colour) is about 10 mm. The weathering of the joint could lead to the disjointing of the bricks.

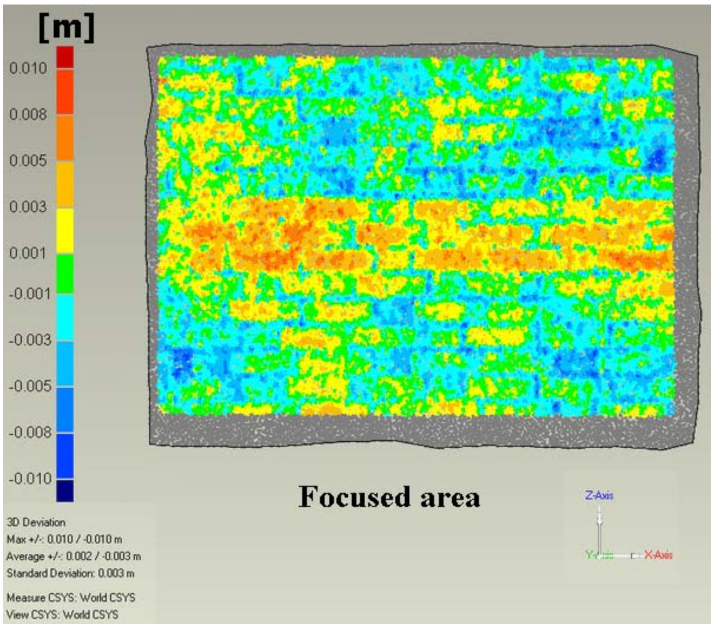

Figure 14. Delamination of bricks and the deterioration of joints detected from the laser scanning data.

For the future work, a repetitive scanning of the wall at the same station and comparing of the results could be a useful method of tracking the progress of the weathering of the joints, the delamination of bricks or the deterioration of the whole wall. Also the development of more algorithms for analyzing the laser scanning data and automated applications for extracting a wide range of features related to building facade deterioration are needed.

Conclusions

Laser scanning is a useful condition survey technique for building surfaces, which provides location based information on the building defects and deterioration.

The terrestrial laser scanning technique is an alternative method for measuring the bowing of cladding panels or elements of the building facades. The bowing of the marble panels could be calculated by fitting a curve to the laser scanning point cloud data. The type of the curve fitting could be determined according to the results of the manual measurements, the visual inspection or the shape of the point cloud data itself. The surface delamination of bricks and the deterioration of joints can also be detected using the laser scanning system.

For the future work, a repetitive scanning for tracking the progress of the deterioration of the building facades and the development of more algorithms for analyzing the laser scanning data and automated applications for exhibiting a wide range of features related to building facade deterioration are needed.

References

[1] Siegesmund, S., Ruedrich, J. and Koch, A. (2008). *Marble bowing: comparative studies of three different public building facades*. Environmental Geology Journal, Springer Berlin / Heidelberg, Vol. 56, Numbers 3-4 / December, 2008. Pages 473–494.

[2] Hiremagalur, J., Yen K.S., Akin K., Bui T., Lasky T.A., Ravani B. (2007). *Creating standards and specifications for the use of laser scanning in caltrans projects.* AHMCT Research Center, UCD Dept of Mechanical & Aeronautical Engineering Davis, California, USA. Available online at: http://www.ahmct.ucdavis.edu/images/AHMCT_LidarFinalReport.pdf [Accessed 25.10.2009].

[3] El khrachy, I. (2007). *Towards an automatic registration for terrestrial laser scanner data*. PhD. thesis. Institute of geodesy and photogrammetry, Technical university Braunschweig, Germaney.

[4] Liya T. (2006). *Automated Detection of Surface Defects on Barked Hardwood Logs and Stems Using 3-D Laser Scanned Data*. Doctoral Dissertation. Faculty of the Virginia Polytechnic Institute and State University. Available online at: http://scholar.lib.vt.edu/theses/available/etd-09202006-145847/unrestricted/dissertation-lithomas-06.pdf [Accessed 25.10.2009].

[5] Van Gosliga, R., Lindenbergh, R., Pfeifer, N. (2006) *Deformation analysis of a bored tunnel by means of terrestrial laser scanning*, ISPRS Technical Commission Symposium, September 2006, Dresden, Germany. International Archives of Photogrammetry, Remote Sensing and Spatial Information Systems, Volume XXXVI, Part 5, pages 167–172.

[6] Grelk, B., Christiansen, C., Schouenborg, B. and Malaga K. (2007). *Durability of Marble Cladding – A Comprehensive Literature Review*. Journal of ASTM International, Vol. 4, No. 4. Available online at: http://www.astm.org/JOURNALS/JAI/PAGES/289.htm [Accessed 25.10.2009].

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