www.itcon.org - Journal of Information Technology in Construction - ISSN 1874-4753

MEASURING THE BOWING OF MARBLE PANELS IN BUILDING FACADES USING TERRESTRIAL LASER SCANNING TECHNOLOGY

PUBLISHED: January 2010 at http://www.itcon.org/2010/4
EDITOR: B-C Björk

Fahim Al-Neshawy, Lic.Sc. (Tech.),
Jukka Piironen, M.Sc. (Tech.),
Susanna Peltola, M.Sc. (Tech.),
Department of Structural Engineering and Building Technology, Helsinki University of Technology, Finland;
firstname.lastname@tkk.fi

Anna Erving, M.Sc. (Tech.),
Nina Heiska, MA (Archaeology),
Milka Nuikka, M.Sc. (Tech.),
Institute of Photogrammetry and Remote Sensing, Helsinki University of Technology, Finland;
firstname.lastname@tkk.fi

Jari Puttonen, Professor of Structural Engineering and Building Technology, Helsinki University of Technology, Finland;
firstname.lastname@tkk.fi

SUMMARY: *Natural stones are widely used as building facade materials. Numerous cases of damage indicate that their deterioration depends mainly on ambient climate. The marble claddings in some cases are known to bow, expand and lose their strength when exposed to weathering. Depending on the bowing, panels may show cracks mostly initiated at the dowels. The percentage of visible cracks and breakouts increases with the amplitude of bowing. The objective of this paper is to find a potential use for the terrestrial laser scanning technique in detecting the deterioration of the building facades and in measuring quantitatively the dimensions of the damaged areas. This paper focuses on detecting the bowing of marble cladding of building facades. Field measurements were carried out using a terrestrial laser scanner. The measurements of the bowing of the marble panels were also carried out manually with a so-called "bow–meter". The results show that the terrestrial laser scanning technique gives an accurate and reasonable method for measuring the bowing of marble panels of the building facades. The terrestrial laser scanning is not a replacement for existing condition survey techniques, but an additional method. The terrestrial laser scanning can be employed to complete many surveying tasks on large surfaces because of the spatial coverage of the point cloud, and the non-touching measurement principle.*

KEYWORDS: *Laser scanning, Deterioration, Inspection, Marble panels, Building Facades.*

REFERENCE: *Al-Neshawy F, Piironen J, Peltola S, Erving A, Heiska N, Nuikka M, Puttonen J (2010) Measuring the bowing of marble panels in building facades using terrestrial laser scanning technology, Journal of Information Technology in Construction (ITcon), Vol. 15, pg. 64-74, http://www.itcon.org/2010/4*

1. INTRODUCTION

Durability is an important issue to consider when choosing stones as cladding material for exterior exposure. The use of stone panels as cladding materials for facades has undergone a considerable increase in the last decades. Durability problems of marble claddings focus on the most significant deterioration feature known as the bowing behaviour. An example of the bowing of marble panels on a building facade is shown in FIG. 1. The reasons for the deformation of the marble panels could be the thermal micro-fracturing of marble, the freezing and thawing cycles, the variation of moisture contents and the combined effect of temperature cycles under the presence of moisture (Siegesmund et al. 2008).

FIG. 1: Example of the clearly developed convex bowing of marble panels (Siegesmund et al. 2008).

Structural condition monitoring is an important methodology in evaluating the condition of a structure by assessing the level of deterioration and the remaining service life of the structures. Today terrestrial laser scanning has been applied to structure condition monitoring. This technique allows the fully remote acquisition of a surface with the sampling step of one centimetre step and is, therefore, able to detect deformations. The key of the proposed method is based on curvature analysis of Terrestrial laser scanning based data and is aimed to recognize the surface defects of the structure. (Teza et al.2009)

The Terrestrial laser scanning technology has been developed a lot in the recent years. The scan speed exceeds tens of thousands points per second. High performance scanners are used widely to record defect information and structural damage. The detailed information of the defects recorded by the 3-D laser scanners can be used in digital format. The digitized image can be manipulated further by using colouring schemes to magnify the defects. (Chang et al. 2008) As a result, the terrestrial laser scanning is becoming more feasible as a data collection method for applications in different industrial and construction fields.

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. (Liya 2006) & (Van Gosliga et al. 2006)

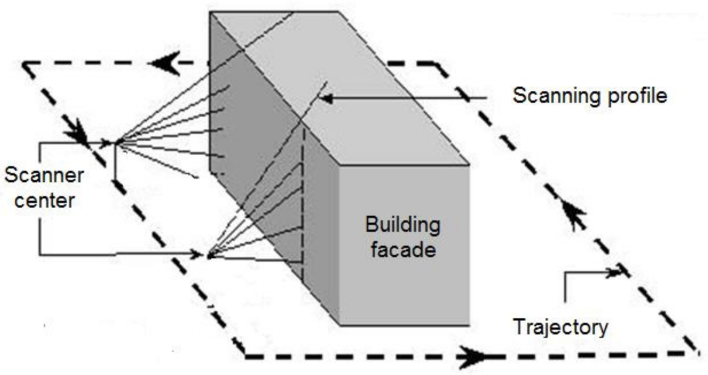


FIG. 2: The principle of terrestrial laser scanning of building facades.

Terrestrial laser scanning is a special technique in which the building is scanned as shown in Fig. 2. The result is a high-resolution cloud of points. The terrestrial laser scanning systems use a directed laser beam for distance measurement to collect spatial information. A laser scanner creates a model of a large number of points with x y z coordinates. The point cloud is a regularly sampled spatial representation of the real world. The x y z coordinates relate the points measured on real world objects to the origin of the scanner, or more often to a project coordinate system used to tie several scans together. The ability of a laser scanner to capture large amounts of data quickly and with a fine resolution means that the real world can be accurately modelled. [Bornaz et al 2004]

2. FIELD MEASUREMENTS AND DATA ANALYSIS

Field measurements were carried out using a terrestrial laser scanner. A flow chart for the execution sequence of the terrestrial laser scanner technique is shown in Fig. 3.

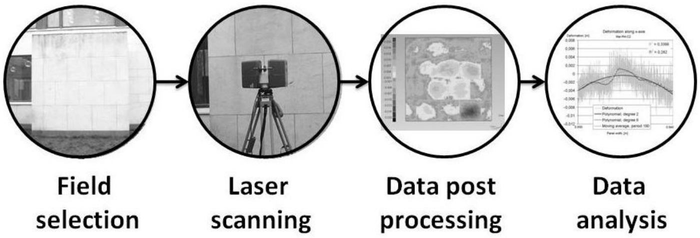


FIG. 3: Flow chart of the laser scanning technique.

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. Geomagic Qualify software was used for further analysing and determining the surface delamination and the joints decaying of the masonry facade. Measurements of the bowing of the marble panels were also carried out manually with a so-called “bow–meter”.

2.1 Field measurements

For the field measurements, the marble panels of a wall at Helsinki University of Technology (TKK) were selected, shown in Fig. 4.

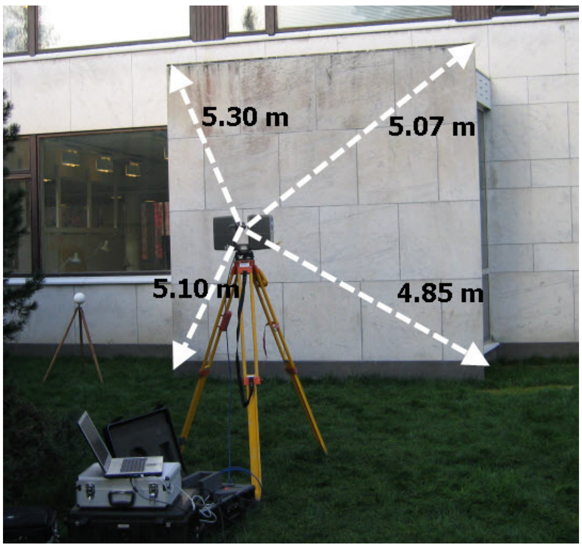
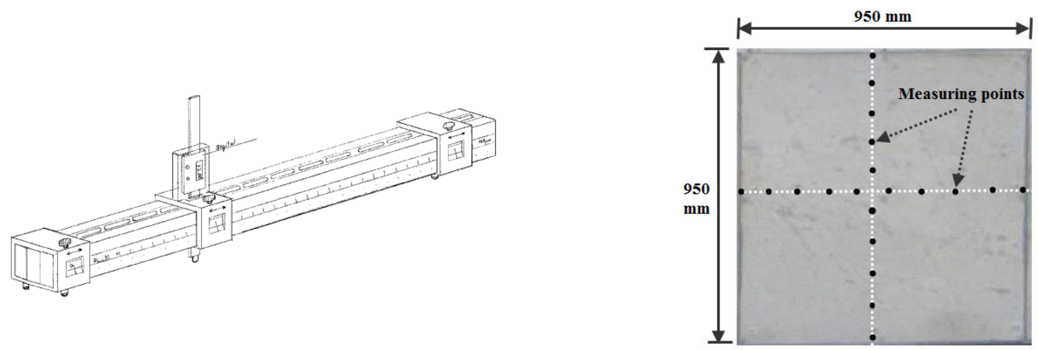


FIG. 4: The marble wall of the department of Architecture at TKK

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 marble wall was scanned from one position without overlapping measurements. The scanner was located 4.36 m from the centre of the marble wall. The systematic distance error is +/- 3 mm. The achieved pixel resolution for the terrestrial laser scanner was approximately a 1 mm point spacing (grid), when the scanner was approximately four meters away from the object. In terms of rangefinder repeatability, the manufacturer of the FARO LS 880HE80 terrestrial laser scanner specifies ±2.6 mm and ±5.2 mm for 90% and 10% reflectivity respectively, at a 10 m range. At a 25 m range, the repeatability for 90% is ±4.2 mm and for10 % it is ±10 mm The scan angle accuracy for the FARO LS 880HE80 scanner is ±0.009°.

Filtering noise and deleting additional and unnecessary points from the point cloud were performed with FARO Scene software; 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.

The measurements of the marble panels bowing were also carried out with the so-called “bow–meter”. shown in Fig. 5.a. The “bow–meter” 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 measurement accuracy of the bow-meter is ± 0.2 mm. The bowing of the marble panel was measured in the vertical and the horizontal direction as shown in Fig. 5.b.



(a) (b)

FIG. 5: Manual measurement of the bowing of marble panels: a) Sketch of the bow-meter and b) the location of the measuring points on the marble panel.

2.2 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. [Grelk et al. 2007] The bowing magnitude of marble panels was calculated using equation 1.

$$B = \left(\frac{d}{L}\right) * 1000 \quad (1)$$

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 quadratic polynomial curve for the vertical and the horizontal bowing are shown in Fig. 6.

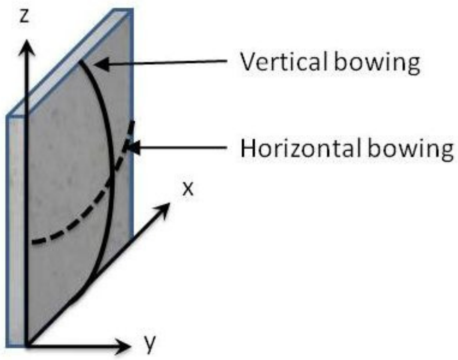


FIG. 6: The quadratic polynomial curves for the vertical and the horizontal bowing of the marble panel.

The polynomial equation of the vertical bowing is:

$$f(z) = a_2 * z^2 + a_1 * z + a_0 \tag{2}$$

where:

z is a variable of the panel height and

the unknown coefficients a_2, a_1, and a_0 are calculated using equation 3.

$$\begin{pmatrix} a_0 \\ a_1 \\ a_2 \end{pmatrix} \begin{pmatrix} 1 & z_1 & z_1^{\ 2} \\ ... & .. & ... \\ 1 & z_n & z_n^{\ 2} \end{pmatrix} = \begin{pmatrix} y_1 \\ ... \\ y_n \end{pmatrix} \tag{3}$$

The polynomial equation of the horizontal bowing is:

$$f(x) = b_2 * x^2 + b_1 * x + b_0 \tag{4}$$

where:

x is a variable of the panel width and

the unknown coefficients b_2, b_1, and b_0 are calculated using equation 5.

$$\begin{pmatrix} b_0 \\ b_1 \\ b_2 \end{pmatrix} \begin{pmatrix} 1 & x_1 & x_1^{\ 2} \\ ... & .. & ... \\ 1 & x_n & x_n^{\ 2} \end{pmatrix} = \begin{pmatrix} y_1 \\ ... \\ y_n \end{pmatrix} \tag{5}$$

The horizontal and vertical bowing of marble panels was calculating 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. An example of the polynomial curve fitting of terrestrial laser scanning point cloud data of the horizontal centre line of the marble panel is shown in Fig. 7.

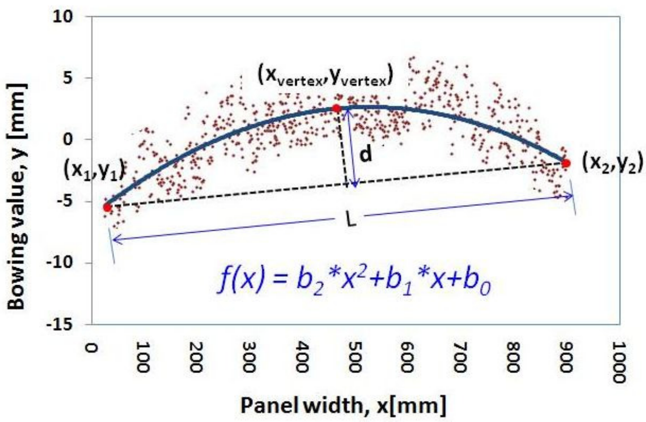


FIG. 7: Example of the polynomial curve fitting of the terrestrial laser scanning point cloud data.

The value of the measuring distance between the supports of the marble panel was calculated with equation 6.

$$L = \sqrt{(y_2 - y_1)^2 + (x_2 - x_1)^2}\text{ , (mm)} \tag{6}$$

where :

(x_1, y_1) = the first point in the fitted quadratic polynomial curve and $y_1 = b_2 * x_1^{\ 2} + b_1 * x_1 + b_0$

(x_2, y_2) = the last point in the fitted quadratic polynomial curve and $y_2 = b_2 * x_2^{\ 2} + b_1 * x_2 + b_0$

b_2, b_1 and b_0 are calculated with equation 5

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:

$$x_{vertex} = \frac{-b_1}{2b_2} \tag{7}$$

$$y_{vertex} = f\left(\frac{-b_1}{2b_2}\right) = b_2 * \left(\frac{-b_1}{2b_2}\right)^2 + b_1 * \left(\frac{-b_1}{2b_2}\right) + b_0 = -\frac{b_1^{\ 2}}{4b_2} + b_0 \tag{8}$$

The measured value of bowing of the marble panel in (mm) is calculated with equation 9.

$$d = \left(y_{vertex} - y_1 - \left(\frac{y_2 - y_1}{x_2 - x_1} * (x_{vertex} - x_1)\right)\right) * \left(\frac{(x_2 - x_1)}{\sqrt{(y_2 - y_1)^2 + (x_2 - x_1)^2}}\right)\text{ , (mm)} \tag{9}$$

The bowing magnitude of marble panels calculated with equation 1.

3. RESULTS AND DISCUSSION

The field measurements of the marble panels mostly show a remarkable convex bowing, as shown in Fig. 8. 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.

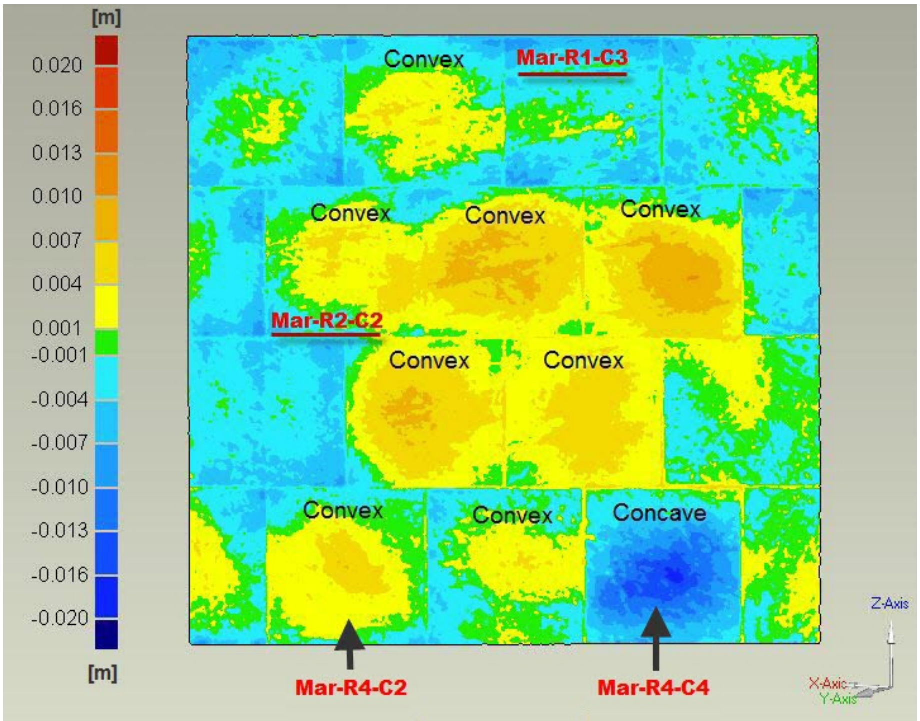


FIG. 8: Terrestrial laser scanning data, colouring by the magnitude of the deformation from the planarity.

The results of the manual measurement of two marble panels using the bow-meter are shown in Figures 9 — 10. 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.

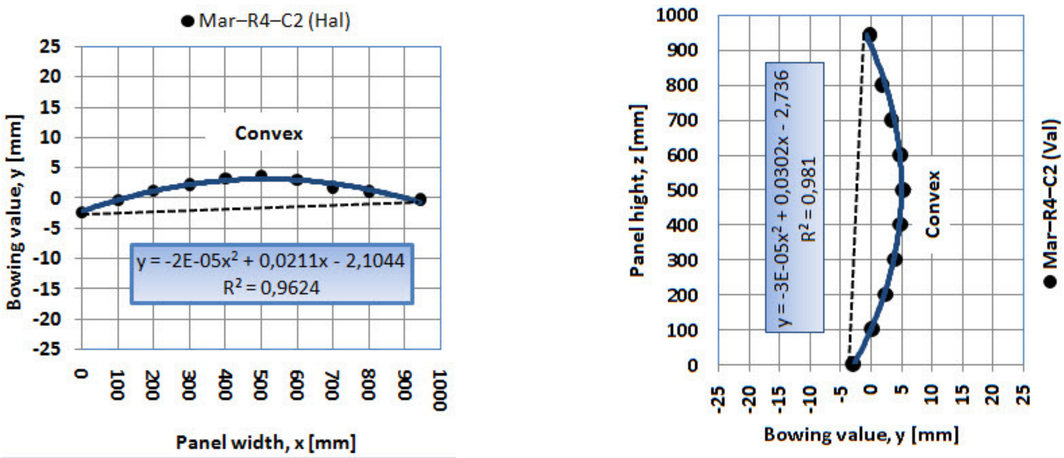


FIG. 9: The manual measurements of the bowing of the marble panel Mar-R4-C2.

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.

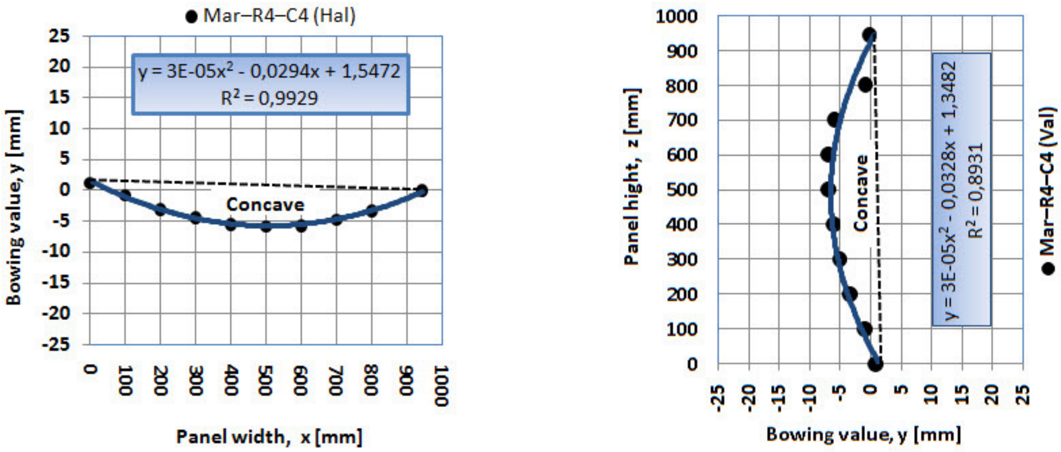


FIG. 10: The manual measurements of the bowing of the marble panel Mar-R4-C4.

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.

Some examples of the bowing in the marble panels are shown in table 1 and Figures 11 – 14. The polynomial curve fitting of the laser scanning point cloud data for the centre line of the panel "Mar-R1-C3" shows a slight bowing of the panel. The vertical direction bowing value is 2.1 mm and the horizontal direction value is 3.6 mm. The standard deviations of the cloud point fitting to the curve are 2.8 mm on the vertical direction and 3.8 mm on the horizontal direction. The second order curve fitting to the laser scanning point cloud data in the vertical and the horizontal directions shows low (0.51 and 0.13) coefficients of determination due to the scattering of the point cloud data. A slight bowing is measured in the horizontal direction of the panel "Mar-R2-C2".

The maximum convex bowing magnitude was measured on the horizontal direction of the panel "Mar-R2-C2". The magnitude (of the bowing) is 8.5 mm (L/100) 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, manual measurement and the curve fitting of the laser scanning point cloud data. The horizontal and vertical bowing values of the panel "Mar-R2-C2" are 11.2 mm (L/85) and 14.3 mm (L/65) 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 0.81.

TABLE 1: 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–R1–C3	Horizontal	955	3.6	3.8	Convex	4
	Vertical	930	2.1	2.8	Convex	2
Mar–R2–C2	Horizontal	915	3.4	2.0	Convex	4
	Vertical	870	5.6	2.3	Convex	6
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

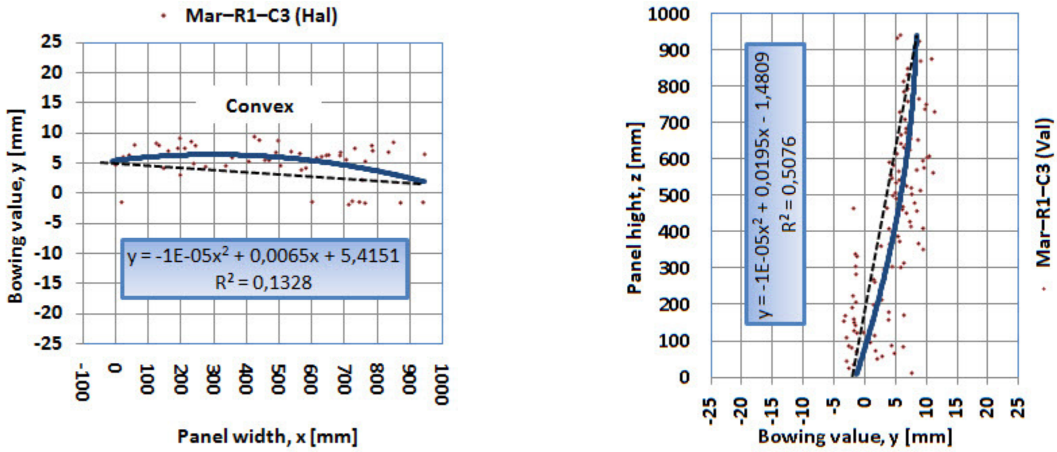


FIG. 11: The horizontal and vertical bowing in marble panel Mar-R1-C3.

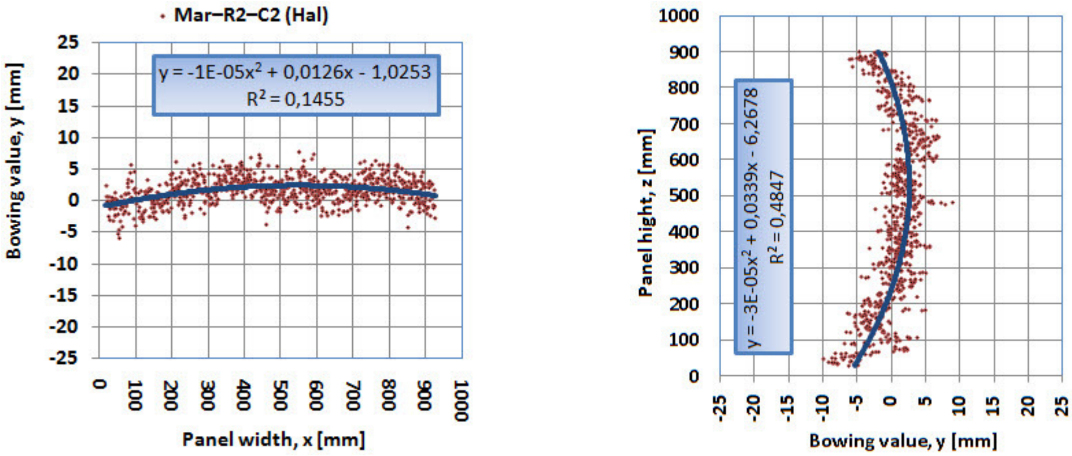


FIG. 12: The horizontal and vertical bowing in marble panel Mar-R2-C2.

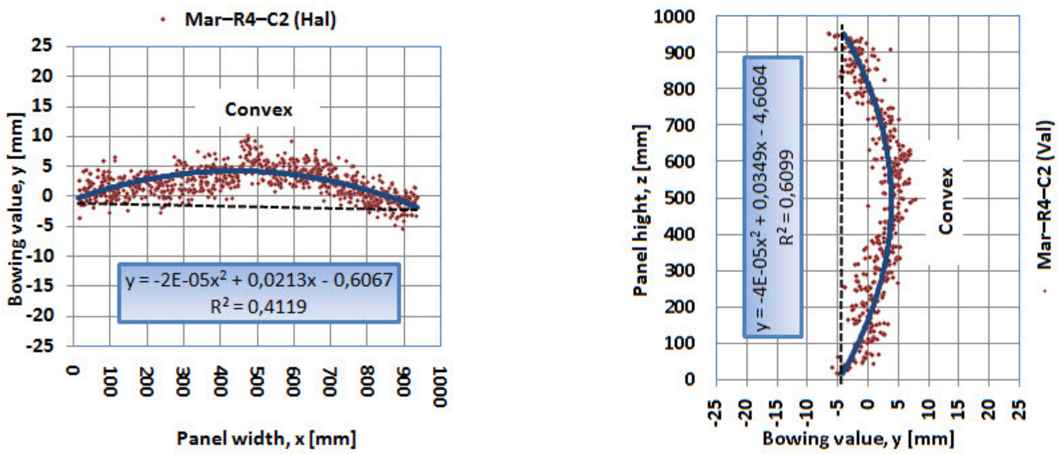


FIG. 13: The horizontal and vertical bowing in marble panel Mar-R4-C2.

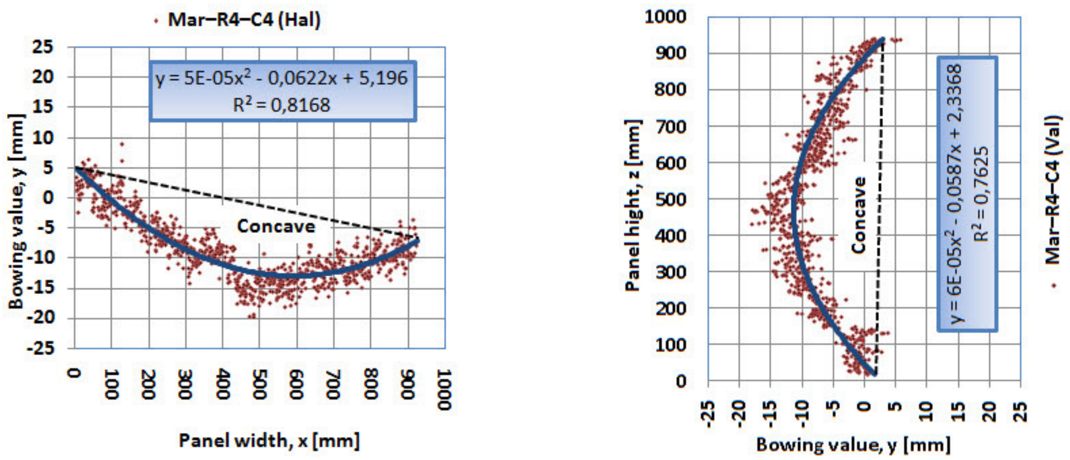


FIG. 14: The horizontal and vertical bowing in marble panel Mar-R4-C2.

Table 2 presents the results of the onsite bowing measurements using the terrestrial laser scanner and the bow-meter. The comparison of these results showed a difference of 1 – 2 mm/m for the convex bowing magnitude and 6 –7 mm/m for the concave bowing magnitude.

TABLE 2: Comparing the bowing magnitudes of two marble panels using laser scanning and bow-meter.

Marble panel	Type of bowing	B/TLS (mm/m)	B/bow-meter (mm/m)	$B_{TLS} - B_{bow\text{-}meter}$ (mm/m)
Mar–R4–C2	Horizontal convex	+6	+5	+1
	Vertical convex	+9	+7	+2
Mar–R4–C4	Horizontal concave	-12	-6	+6
	Vertical concave	-15	-8	+7

The magnitude of convex bowing (B = +6 – +9 mm/m) was measured on the panel "Mar–R4–C2". The magnitude of concave bowing (B = -12 – -15 mm/m) was measured on the panel "Mar–R4–C4". The high magnitude of the concave bowing could be due to the failure of the panel anchoring to the wall.

4. CONCLUSIONS

In this paper, the bowing of marble cladding panels of a wall at Helsinki University of Technology using laser scanning technology was investigated. The field work was carried out with manual bow-meter and FARO LS 880HE80 terrestrial laser scanner.

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 both in the vertical and the horizontal directions. 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 comparison between the results from the laser scanning and the bow-meter showed only a slight difference in measuring the convex bowing magnitude and quite a high difference in measuring the concave bowing magnitude.

Laser scanning is not a replacement for existing condition survey techniques, but an additional method, which provides location based information on the building defects and deterioration.

5. REFERENCES

Bornaz. L. and Rinaudo. F. (2004). Terrestrial Laser Scanner Data Processing. International archives of photogrammetry remote sensing and spatial information sciences. Vol. 35. Part 5. pp. 514–519.

Chang K-T.. Wang E.. Chang Y-M. and Cheng H-K. (2008). Post-Disaster Structural Evaluation Using a Terrestrial Laser Scanner. FIG Working Week 2008. 14 – 19 June 2008. Stockholm. Sweden. Available online at: http://www.fig.net/pub/fig2008/papers/ts05c/ts05c_06_chang_etal_2905.pdf [Accessed 14.10.2008].

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 14.10.2008].

Hall D. (2008). Building defects. Inspections and Reports. Available online at: http://www.buildingdefects.com.au/defect-salt-deterioration.html [Accessed 14.10.2008].

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 14.10.2008].

Newman A. (2001). Structural Renovation of Buildings: Methods. Details. and Design Examples. *McGraw-Hill. New York.* Pp 505–539.

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. Pp 473–494.

Teza. G.. Galgaro A.. Moro F. (2009). Contactless recognition of concrete surface damage from laser scanning and curvature computation. NDT&E International Volume 42. Issue 4. June 2009. Pp 240–249.

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. Pp 167–172.