Some laser-scanner applications in structural analysis

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Abstract: In the present work, the authors intend to describe some recent experiences in the application of the laser scanner technique to the structural analysis. Three main examples are provided, the former involves a typical Renaissance Palace in Ferrara, the second one is developed in the framework of the damage analysis carried out for the Nativity Church in Bethlehem, and the latter deals with the non-destructive testing of a common historical masonry building in Ferrara. In such examples the laser scanner data acquisition is mainly aimed at investigating the structural behaviour and not at the geometrical representation. The contribution ends with some comments on the current open issues.

Keywords: laser scanner; data acquisition; structural analysis; structural monitoring.

Reference to this paper should be made as follows: Alessandri, C. and Mallardo, V. (xxxx) 'Some laser-scanner applications in structural analysis', *Int. J. Masonry Research and Innovation*, Vol. X, No. Y, pp.xxx–xxx.

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1 Introduction

Most of the applications of the laser scanner technique to the civil engineering field are mainly focused on the acquisition of the geometry of the structure. Such an acquisition requires plenty of post-processing ‘extra’ work before being suitably adopted in a readable format. Surface reconstruction, three-dimensional modelling, horizontal and vertical sections plotting are some of the steps that are to be carried out in order to provide clear drawings. Even more difficult, currently very hard, is the extra work that is necessary to import the data into any structural analysis software or simulation (Auciello and Ercolano, 1997). The issue is complicated by the assumption that, at present, the laser scanner allows the acquisition of the external skin of the structure, and, thus, the cloud of points is spoiled by non-structural elements (such as walls in reinforced concrete buildings, plaster, cornices, tiles, etc.). This is the reason why most of the applications in the literature refer to masonry structures, where at least the vertical bearing elements may be given by visible masonry walls, the horizontal slabs are, often, supported by visible wood beams and the vaults may be free of lining and characterised by complex curvatures (Contestabile et al., 2016).

In Lubowiecka et al. (2009) the terrestrial laser scanner was used to document and analyse some historical masonry bridges in Galicia, a region in Northwest Spain. One bridge was analysed in the paper. It has five pointed arches with the longest span of 11.5 m and the laser scanning was first set to 2 cm of resolution in order to provide its complex geometry. In Wittich et al. (2015) a broad field survey of 24 human-form statues was carried out. Geometric data was acquired with image-based processes and laser-scanning processes and the 3D digital reconstructions compared; a resolution of around 6 mm was set and six-seven scans per statue were performed. In Manfredi et al. (2013) the geometric survey of a vaulted structures was carried out using a help-assisted total station with cylindrical targets. The data was referred to a highly damaged 18th century building complex in the city of Nola (near Naples) in the South of Italy. The cloud of points was deeply post-processed in order to extract horizontal and vertical sections from which a 3D structural model might be built independently. In Barbieri et al. (2013) the exact geometry of a historic masonry building in Mantua (Italy) was detected by some laser scanner measurement campaigns carried out in two years with a high resolution ranging between 2.0 and 4.0 millimetres. The scanning was mostly concentrated to the main façades of the building. In Bednarz et al. (2014) the whole interior of an historical presbytery church in Poland was detected by a high-definition surveying 3D laser scan. In Chellini et al. (2014) a 3D outer and inner model of a Church in Barcelona (Spain) was obtained by performing a 4-mm accuracy laser scanning.

All the above contributions use the geometrical survey obtained by laser scanner to perform some structural numerical analyses, and all the authors underline the difficulties to carry out such a task. Alignment, cleaning and segmentation, triangulation and so on, are first performed to obtain clear drawings, usually in CAD format. The construction of the 2D or 3D structural (FEM) model is usually carried out manually. Even if recent developments allow the automatic conversion of the cloud-of-point model into a NURBS-based structural mesh model (see Beer, 2015 for instance) both in FEM (see Cottrell et al., 2009) and in BEM (see Beer et al., 2017), the issue has not been automatised so far and it is still open.

Last but not least, the work by Gordon and Derek (2007) is worthy of being mentioned as the laser scanner was involved to measure the vertical displacement of beams undergoing controlled loading. Therefore, this work can be considered an application aimed at non-destructive structural monitoring and not at geometry acquisition, since destructive tests involve significant efforts (Calderoni et al., 2010). A similar goal was pursued in Barbieri et al. (2013) where the laser scanner data was used to monitor the magnitude of the inclination of the longitudinal walls.

On the basis of some recent experiences carried out by the authors (see Mallardo et al., 2008; Alessandri and Mallardo, 2012; Alessandri et al., 2012, 2015), the present work intends to present some applications of the laser scanner technique both to the structural analysis and to the non-destructive structural monitoring.

2 Laser scanner as first step of structural analysis

A 3D laser scanner survey was carried out by the authors on a typical Renaissance historical Palace in Ferrara (see Mallardo et al., 2008). A digital survey was carried out by using a 3D laser scanner equipment, that is Leica HDS Cyrax 3000, based on a time-of-flight technology supplying 1,000–1,800 points per second with the precision of 5–6 millimetres and viewing ranges of up to 360° × 270°.

The data acquisition was mainly focused on the main façade of the palace in order to obtain the geometry representation as well as any important structural information (lack of verticality, presence of holes, etc.). Some of the results from the 3D survey campaign are shown in Figure 1. The scan of the façade was carried out by means of three stations (located at the centres of each third of the façade length) and with a two-fold accuracy (5 × 5 cm and 2.5 × 2.5 cm grids). The façade is 70 m long and 12 m high.

Figure 1 (a) Dot clusters of the courtyard and (b) of the main façade (see online version for colours)

(a) (b)

The 3D-laser-scanner output needed to be processed iteratively in order to provide a 3D CAD geometrical model to be used in the F.E. context. The issue was simpler when the main façade was investigated. In fact, it was easier to build a plane model from the laser scanner output.

Figure 2 (a) F: equivalent frame model, C: Adina 2D mesh, L: homogenised limit analysis discretisation (b) Global structural response (see online version for colours)

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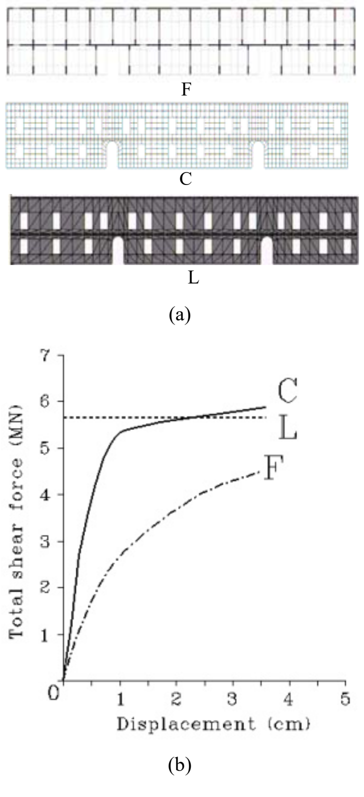
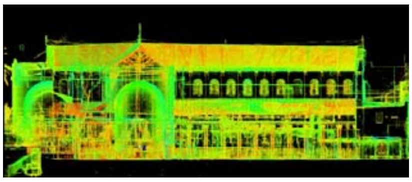


A seismic analysis was then carried out on the wall to measure its vulnerability. Three approaches were used: equivalent frame model (F), inelastic plane stress model (C) and a homogenised limit analysis (L). Mesh adopted and global numerical results are depicted in Figure 2.

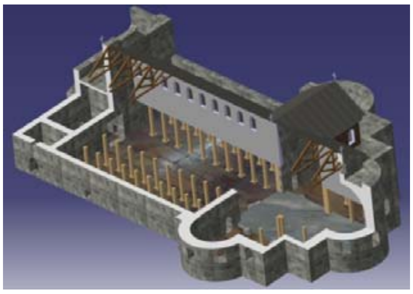
It must be pointed out that both steps, from laser scanner data to CAD format and from CAD format to the structural analysis, required many men-hours to be carried out as classical discretisation strategies were adopted (Minutolo et al., 2009; Ruocco and Mallardo, 2013; Ruocco and Minutolo, 2015).

A similar approach was carried out in the analysis of the Nativity Church in Bethlehem in the years 2009–2012 (see Alessandri and Mallardo, 2012 and Alessandri et al., 2012). Such a study was mainly aimed at investigating the structural safety level of the Church with special attention to its seismic vulnerability (Calderoni et al., 2011) and to the roof wooden trusses, the latter deeply damaged by copious rainwater infiltrations.

Figure 3 (a) Snapshot of the laser scanner survey (b) Three-dimensional view of the church obtained by the laser scanner survey (see online version for colours)



(a)



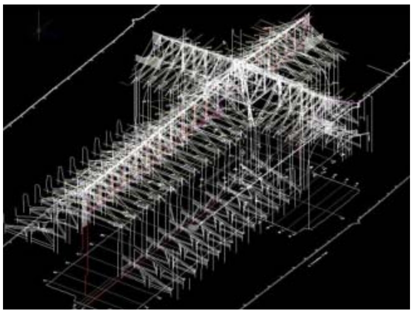
(b)

The laser scanning survey (see Figure 3) was useful to obtain a detailed measurement of the geometry of the main wall, that is the wall bearing the roof and transferring its weight to the columns below, the precise acquisition of the dimensions of the roof wooden elements [see Figure 4(a)], and the accurate survey of the complex system of underground grottoes. The whole data were obtained by selecting 110 different scanner positions and by using a 3D high definition laser scanner Leica, model HDS3000 (grid varying from 5 × 5 to 10 × 10 cm, with some focus of 2.5 × 2.5 on special areas).

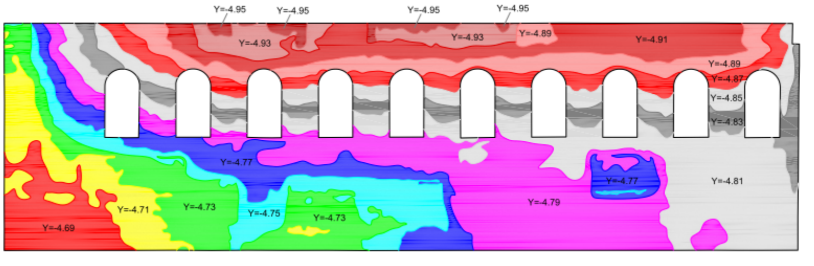
The above data allowed to get the correct value of the structural safety level of the wooden beams as it was enriched by any area variation along the main axis and by the presence of defects and knots. Such an analysis allowed to design a less invasive intervention solution as the geometry definition had no uncertainties, thus minimising the wood parts to be replaced.

The laser scanner data acquired from the main wall (with a grid of 2.5 × 2.5 cm and two different stations on each side of the wall) produced the description of the out-of-plane effects on the internal surfaces depicted in Figure 4(b). It was thus possible to measure the amplitude of the out-of-plane difference between the top and the bottom, that is 26 cm, and to keep such a difference into account in the structural safety analysis of the seismic out-of-plane mechanisms. The out-of-plane leaning was around 3.3% of the height of the wall (8 m), but more than a half was concentrated in the first top 4 metres thus providing a slope of around 5%. It is worthy to observe that a similar approach was carried out in Barbieri et al. (2013) to investigate the magnitude of the inclination of the longitudinal walls of a historic masonry building in Italy (Guadagnuolo et al., 2014).

Figure 4 (a) Snapshot of the laser scanner survey of the roof beams (b) Contour plot of the y-position, south wall as seen from the nave (see online version for colours)

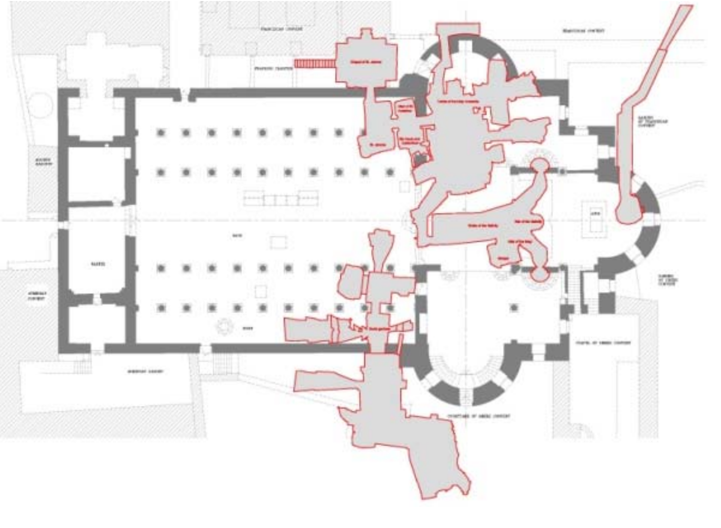


(a)



(b)

Figure 5 Plan of the grottoes under the church (see online version for colours)



The laser scanning survey found its best application in the survey of the underneath grottoes (see Figure 5). The absence of finings and the well-known high complexity in the alternative manual mapping, make the laser scanning an excellent alternative. The output data were obtained with 25 different stations and a grid of 10 × 10 cm as the required detail was rather coarse.

The data were useful to perform the structural analysis of some meaningful 2D sections of the grottoes and to provide a more realistic measure of the safety level in the areas of the church subjected to the highest crowding of pilgrims.

3 Laser scanner as non-destructive monitoring tool

Most of the work dealing with the intersection between laser scanning and structural analysis is focused on the geometry acquisition and on the procedures to carry out to import the data in any structural software. As a matter of fact, structural monitoring would benefit from a long-term laser scanner acquisition, but the applications of laser scanning to structural monitoring are very few.

In Bednarz et al. (2014), for instance, three scans of the interior of a presbytery church were generated in three different years (2009, 2011 and 2013) but at the same day and at similar temperature/humidity conditions. The merging of the three scans provided a basis for analysis of the direction of displacement of vault and walls. In Barbieri et al. (2013) some (laser-scanner) measurement campaigns were carried out between 2005 and 2007 to monitor the inclination of some longitudinal walls.

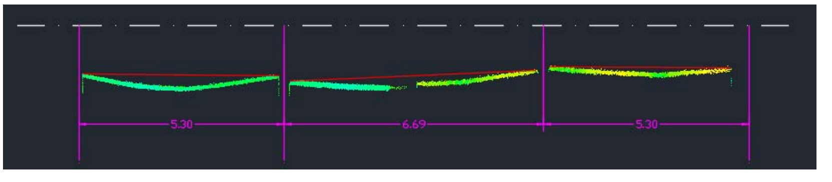
Figure 6 A vertical section provided by the laser scanner acquisition system (see online version for colours)

A very recent application of the authors had a similar objective. The issue was to provide shape and amplitude of the vertical displacement of some horizontal plates in a typical two-floor masonry building in Ferrara. These horizontal plates were designed to bear their weight (tiles, mortar, etc.) and the live load. They were formed by a system of one-direction wooden beams (70 cm spacing) supporting a reinforced (6 mm steel net) concrete slab (6 cm thickness) connected to the beams by bolted triangle trusses.

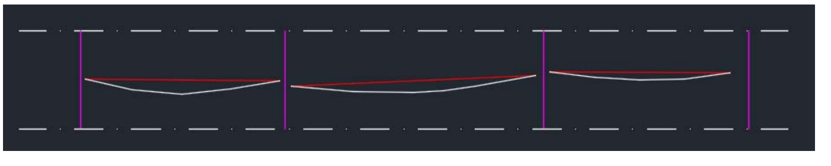
Some visible crack lines had occurred in the tiles of the horizontal slab and the goal of the investigation was to focus on the causes of such cracks, i.e., if related to the structural deflection or to the incorrect laying of tiles and/or underneath substrate.

A laser scanner survey was performed in all the rooms of the building and the acquired data were merged in order to provide meaningful vertical sections (see an example in Figure 6). The cloud of points was first amplified [see Figure 7(a)] and then averaged in order to replace them with lines [see Figure 7(b)]. The final drawing represented the actual position of the bottom external surface of the beams bearing the slab. As the wooden beams were supported at their extremes by thick masonry walls (in Figure 7 located at the intersection with the vertical line), such lines provided a visual representation of the typical vertical deflection of simply-supported beams.

Figure 7 Amplification and lining of the vertical section (see online version for colours)



(a)



(b)

The same procedure was also applied to the upper surface of the slabs. The final lines were able to give the exact vertical position of the tiles along more sections and, thus, to provide some suggestions on the influence of the tile laying phase on the crack occurrence.

4 Conclusions

Nowadays the laser scanner is a geometry acquisition tool that has been experienced many times in conjunction with the structural analysis. Some applications of the authors were described and commented. Still much work is necessary to improve the filtering steps between the cloud of points and the final structural model. A recent step forward has been carried out thanks to the isogeometric approach that would optimise the CAD-CAE step, but no recent breakthrough can be recalled to sort the cloud-olf-point-CAD step out. On the contrary, the technique may have interesting developments in structural monitoring and non-destructive testing. Some experiences of the authors in this field were also presented.

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