Introduction

Heritage buildings are fragile and valuable patrimony of cities and countries. Maintenance and repairing requires efforts and a wide knowledge of the structures. However, in many cases, the constructive methods, the distribution of supporting elements and the materials are unknown. There are two main causes of this uncertainty: the lack of information and drawings due to the age of the buildings, and the misinformation about past restorations, damages and alterations of use and structures.Non-destructive tests are widely used to obtain information since they can be applied without causing any damage [1]. One of the most extended methods in cultural heritage assessment is Ground Penetrating Radar (GPR) [e.g. 2, 3 and 4]. This technique allows a wide and quick evaluation of large parts of the structures. This paper presents examples of data acquisition methods to achieve patterns for further recognition and characterization of structures, materials and damages. The field study was completed in the terraces of *Eixample* of Barcelona, in XIX Century buildings [5 and 6].

In Barcelona, on 1856, Ildefonso Cerdà proposed a plan for the extension of the old city - the so called *Eixample*. The urban plan consisted in a grid of Streets where the blocks of houses were separated by 133.3 m between them. The building height was determined to allow the light enter in the Street. Usually, wooden beams were employed in the construction of the buildings, however in some cases, metal, bricks structures and vaults were also included. The uncertainty causes problems in the maintenance of these buildings. In addition, further changes on the use of the buildings to build up one or even two more levels over the terraces, increasing the weight supported by the structure. These additional weights require a wide knowledge of the structural members in order to determine their maximum possible load. Therefore, GPR was employed to distinguish the constructive elements [7].

Methodology: data acquisition and processing

Common offset radar data was acquired on the terraces of the buildings with an 800 MHz centre frequency antenna. Firstly, the terrace surface was explored with several radar lines, according to the geometry of the surface and the complexity of the detected structure. A number of these lines were perpendicular to the façade and others parallel. The distance between consecutive radar lines was unequal and depended on the existing elements and the shape of the surface. The objective of this irregular grid was to evaluate the structure and locate possible changes in the arrangement and elements. Figure 1 present the radar data acquisition and the plan for both terraces, comprising the radar lines. This procedure allowed distinguishing between homogeneous structural solutions and more heterogeneous structures. In the case of continuous structures, the information from the grid permitted to define the orientation of elements or beams [8, 9 and 10]. The analysis of amplitudes leads to define the material of these structural members, distinguishing between metallic and wooden beams (Figure 2a). Figure 2 b shows the acquired radar images depending on the orientation of the structures related to the radar lines. Furthermore, the position of the antenna was determined with an odometer, with a relative reference from a particular point in the terrace, being the spacing between A-scans 2 cm. Radar images were enhanced with a filtering sequence: zero time correction, background removal, energy decay and DC filtering in order to remove low frequencies.

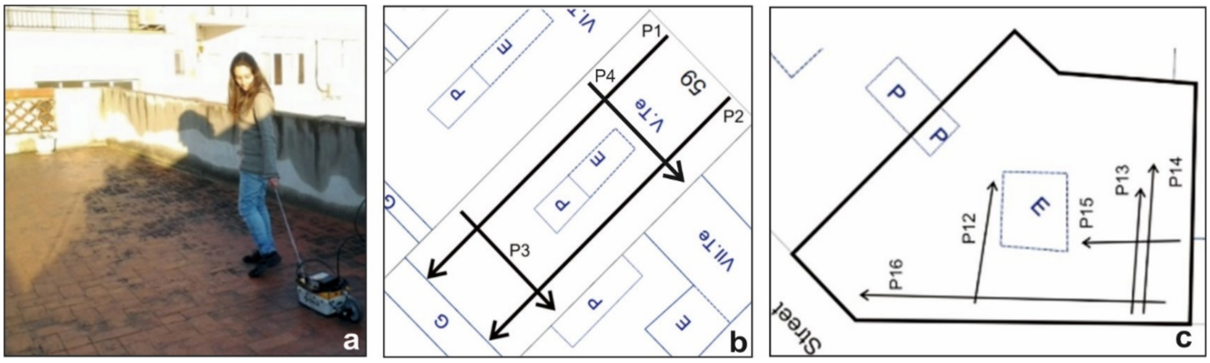

Figure 1 .*a) Radar data acquisition, b) position of radar lines on case 1 c) position of radar lines on case 2.*

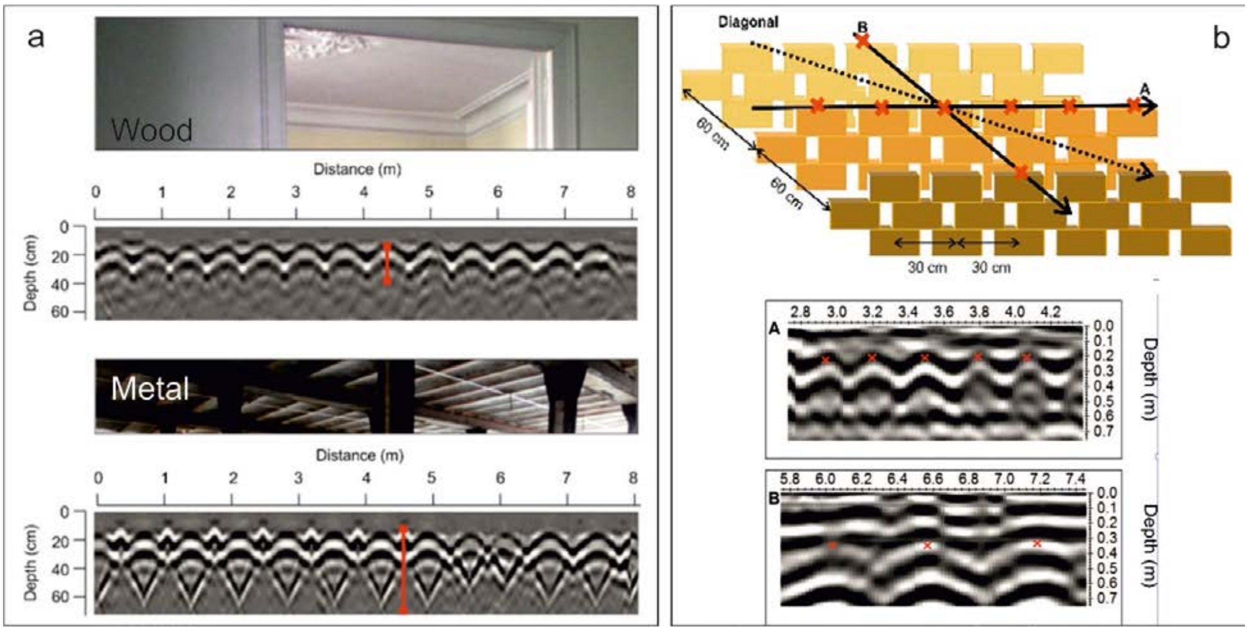

Figure 2.*Radar images from wooden (a) and metallic beams (b), and the effect of the orientation of brick partitions (c) on the radar images (d).*

Results

In this paper two case studies are presented. One of them, case 1, is showing structural changes as consequence of rehabilitation. The position of the profiles for both cases is shown in Figure 1. The other one, case 2, is characterized by significant variation in the built structural supporting structures, including orientation and material types.

Case 1.

In this case, radar image in profile 2 discerns the existence of two walls (Figure 3 a). One of them in the middle of one structure built with masonry partitions and wood, and the other at the end of a reinforced slab included in a restoration. The partitions are clearly defined in this sector located at the beginning of the profile because radar line is perpendicular to the brick walls (see Figure 2), that are found separated 0.5 m apart. The reinforced slab present small hyperbolas produced in rebar. Horizontal resolution permits detecting rebar every 10 cm. The second wall separates the reinforced slab to other zone supported by brick partitions. However, in this case, the orientation of the brick walls changes and is parallel to the radar lines and the profile was carried out in the middle of two partitions. The effect of this arrangement of the structures produces a flat and horizontal anomaly in the radar images, instead of hyperbolas. The B-scan obtained in profile P3 which is perpendicular and crosses P2 between the meters 15 and 16, proves the existence of this particular partition structure (see figure 4c and 4d). In this B-scan also a slab is detected in the middle area at which the stairs are located.

The study allowed defining the position of the partition walls and other structural elements (Figure 3a and 3d). In this case, radar image in profile 2 discerns the existence of two walls (Figure 3b). One of them in the middle of one structure built with masonry partitions and wood, and the other at the end of a reinforced slab. The partitions are clearly defined in this sector located at the beginning of the profile because radar line is perpendicular to the brick walls (see Figure 3b), that are perceived separated 0.5 m apart. The reinforced slab present small hyperbolas produced in rebar. Horizontal resolution permits detecting rebar every 10 cm. The second wall separates the reinforced slab to other zone supported by brick partitions. However, in this case, the orientation of the brick walls changes and is parallel to the radar lines. The effect of this arrangement of the structures produces.

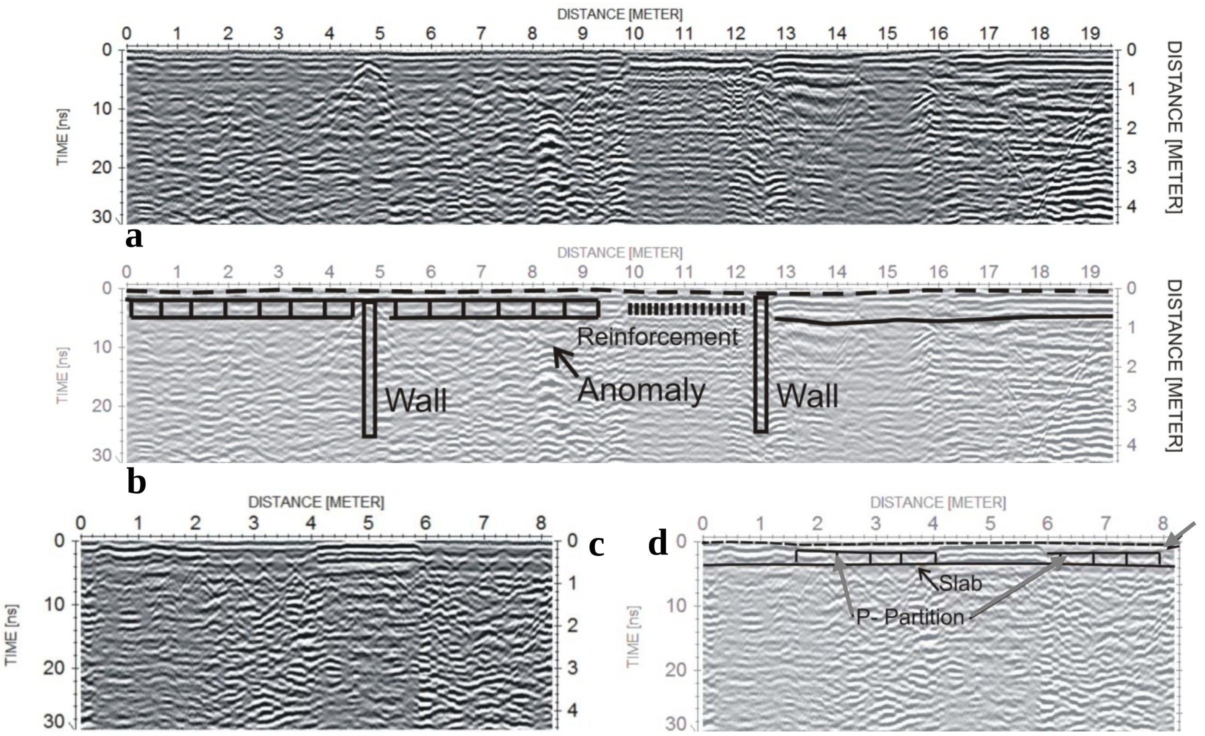

Figure 3. *Radar images in profile P2.a) P2 B-scan. b) P2 radar data interpretation. c) P3 B-scan crossing P2 between its 15 and 16 m. d) P3 radar data interpretation.*

Case 2.

In case 2 the terrace was surveyed through the acquisition of 5 profiles, 2 perpendicular and 3 parallel radar lines to the façade (see Figure 1). The most paradigmatic profile 16 contains chief information about the inner elements present in the terrace (Figure 4). Two walls were clearly identified and half of a third wall is detected right in the beginning of the profile. Above it, it is detected a longitudinal set of parallel elements for the first meters. The following meters GPR data shows an alteration of orientation of the elements. An interesting fact is detected from the middle of the profile towards the end is detection of diagonal walls partition.

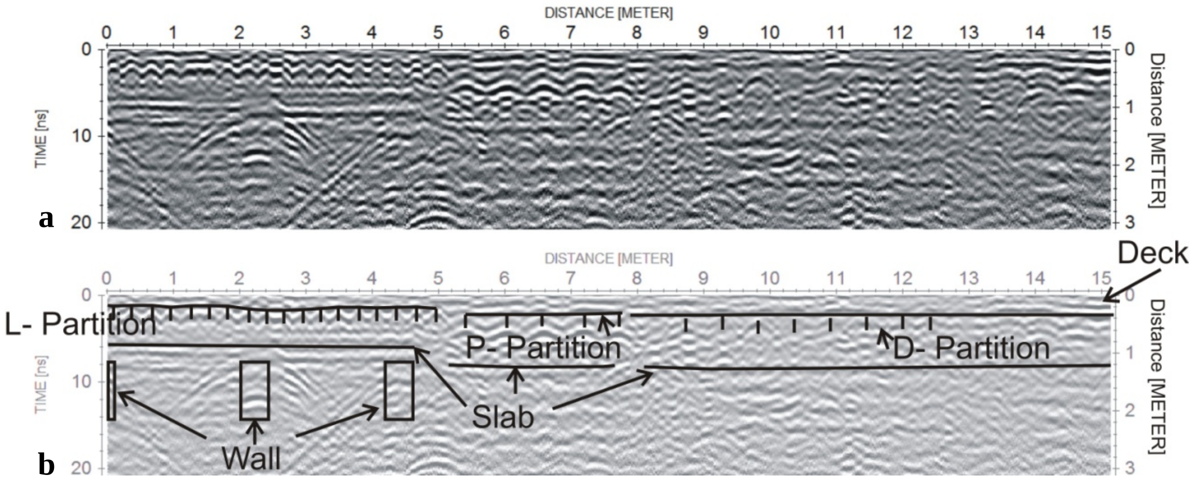

Figure 4. *GPR images in profile 16 a) raw data, b) data interpretation.*

Radar data allowed the description of the arrangement of all the structural supporting structures. Figure 5 shows the structural solutions of the terraces presented in cases 1 and 2. The orientation of the structures is clear and the presence of reinforcement rebar (R in figure 5) is highlighted.

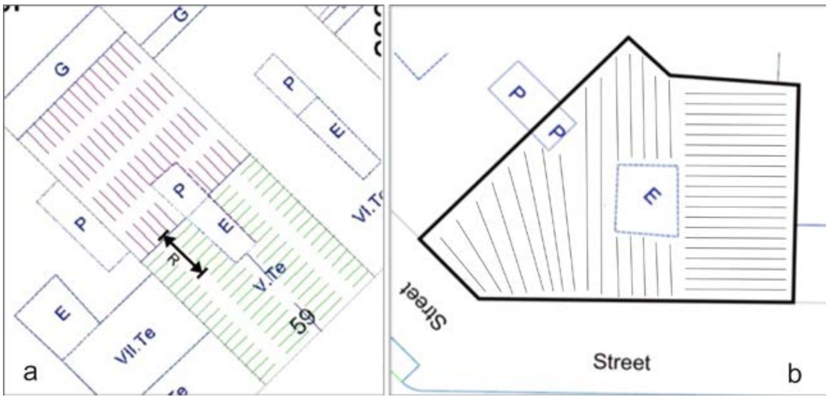

Figure 5. *Structural solution for a) case study 1 and b) case study 2.*

Conclusions

In all cases GPR data supplied information to determine the structural arrangement of embedded element and differentiate between wood and metal targets. These GPR images were valuable in order to establish the maximum supplementary load that the building can bear. Furthermore, information structural alterations (damage, previous restoration or other modifications) were successfully identified and documented from the GPR images. The employed method and respective output results may be applied to civil engineering, architecture, especially to historically heritage buildings.

Acknowledgements

This research has been partially funded by the Ministry of Economy and Competitiveness (MINECO) of the Spanish Government and by the European Regional Development Fund (FEDER) of the European Union (UE) through projects referenced as: CGL2011-23621 and CGL2015-65913-P (MINECO/FEDER, UE). The study is also a contribution to the EU funded COST Action TU1208, “Civil Engineering Applications of Ground Penetrating Radar”.

References

[1] McCann, D. M., & Forde, M. C. (2001). Review of NDT methods in the assessment of concrete and masonry structures. Ndt& E International, 34(2), 71-84.

[2] González-Drigo, R., Pérez-Gracia, V., Di Capua, D., &Pujades, L. G. (2008). GPR survey applied to Modernista buildings in Barcelona: The cultural heritage of the College of Industrial Engineering. Journal of Cultural Heritage, 9(2), 196-202.

[3] Pérez-Gracia, V., Caselles, J. O., Clapés, J., Martinez, G., & Osorio, R. (2013). Non-destructive analysis in cultural heritage buildings: Evaluating the Mallorca cathedral supporting structures. NDT & E International, 59, 40-47.

[4] Kanli, A. I., Taller, G., Nagy, P., Tildy, P., Pronay, Z., &Toros, E. (2015). GPR survey for reinforcement of historical heritage construction at fire tower of Sopron. Journal of Applied Geophysics, 112, 79-90.

[5]Casademunt, A. P. (2009). L'Eixample: secretsd'un sistema constructiu. Universidad Politécnica de Cataluña. *In catalan*

[6] Aibar, E., &Bijker, W. E. (1997). Constructing a city: The Cerdà plan for the extension of Barcelona. Science, technology, & human values, 22(1), 3-30.

[7] Santos-Assunçao, S. (2014). Ground penetrating radar applications in seismic zonation: Assessment and evaluation. Polytechnic University of Catalonia.

[8] Pérez-Gracia, V., Caselles, O., Clapés, J., Osorio, R., Canas, J. A., &Pujades, L. G. (2009). Radar exploration applied to historical buildings: a case study of the Marques de Llió palace, in Barcelona (Spain). Engineering Failure Analysis, 16(4), 1039-1050.

[9] Pérez-Gracia, V., González-Drigo, R., & Sala, R. (2012). Ground-penetrating radar resolution in cultural heritage applications. Near Surface Geophysics, 10(1), 77-87.

[10] Beben, D., Mordak, A., &Anigacz, W. (2012). Identification of viaduct beam parameters using the Ground Penetrating Radar (GPR) technique. NDT & E International, 49, 18-26.