

Masonry Texture Reconstruction through High Frequency 3D GPR

Survey for Building Seismic Assessment

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Abstract

The geometrical texture and morphology of a masonry wall section represent a key parameter when evaluating its seismic response. Such estimate is commonly performed through localised, semi-destructive methods, regarding which Ground Penetrating Radar (GPR) could emerge as an effective alternative survey method, due to its high-resolution, scalable and non-destructive approach. This research has targeted the reconstruction of the geometrical properties of a heterogeneous masonry section through a high-frequency, 3D GPR investigation to evaluate the retrievable information, and the achieved results demonstrated the operational potential of the technique in providing earlier qualitative and quantitative information on the structure seismic behaviour.

Keywords: Ground Penetrating Radar; Seismic assessment; Masonry texture reconstruction; Signal processing; NDT surveys.

1. INTRODUCTION

The definition and characterisation of the texture of a masonry wall represent priority topics not only for building evaluation and diagnosis, but also within the seismic assessment and hazard mitigation domain, as the wall capability of sustaining horizontal in-plane and out-of-plane actions can be estimated provided that the typology, stratigraphy and internal construction and condition of the masonry structure are accurately determined. With all the mentioned attributes available, it is in principle possible to calculate the strength of the investigated masonry as a function of that of the components [1], [2].

Such relevance is enhanced by the fact that earthquake aftermaths are increasingly demonstrating the inefficacies of commonly found masonry textures in preventing the activation of collapsing mechanisms.

26 Even if structural flaws can be principally attributed to improper construction techniques of civil structures in
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27 high seismic risk zones, they are also a direct consequence of the lack of preventive maintenance, as well as
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428 enlargement interventions or structural modifications performed without an adequate historical knowledge of
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629 the building.
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930 It is therefore straightforward that many difficulties could be eliminated if better technical information
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1131 regarding the mechanical characteristics of historic masonry are available. To achieve this scope, it is in
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1432 principle essential to gather as much information as possible to understand how the structure under
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1633 investigation has evolved over time, the modifications, replacements or adjustments that might have taken
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1834 place and the correspondent time period, as these details can guide in formulating assumptions on the
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2035 original construction approach, essential information for estimating the seismic response of the construction.
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2336 In particular, a high percentage of voids in masonry panels and lack of effective connections among
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2537 structural components, as well as low-quality stone units and mortar used in the building process, can lead to
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2738 a degraded seismic resistance. It is therefore straightforward that such constituent materials heterogeneity
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2939 together with the great variability of the possible construction techniques have made it difficult to develop
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3240 reliable modelling schemes, in particular for masonry structures. As a consequence, the described
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3441 information is typically available after the occurrence of a seismic events, which means that the seismic
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3642 assessment of the structure is assessed retrospectively, starting from the damage sustained [3], [4], [5], [6],
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3843 [7]. Although over the years such methodological approach has resulted in the development of highly
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4144 accurate assessment reports [8] that allow to precisely correlate each single structural topology to a specific
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4345 statistical vulnerability index and related seismic hazard curves [9][10][11], it would be important, instead, to
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4546 evaluate the status and vulnerability of a masonry given the intact building, so that targeted interventions can
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4747 be planned and put forward [12].
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5048 It is therefore obvious that in order to qualify the state of preservation of stone or brick masonry walls, a
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5249 knowledge of the inside is essential. The analysis of these structural features is often carried out by locally
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5550 detaching and removing the plaster wall cover to highlight the masonry behind. Given the invasive nature of
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5751 such investigation methodologies, a limited number of samples, typically located in secondary areas of the
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5952 building, are extracted, hence limiting the thoroughness of the assessment and the confidence in claiming
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6153 that the highlighted local behaviour effectively reflects the building as a whole one.
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54 An operational breakthrough within these investigations can be achieved using Ground Penetrating Radar
1 methodology [13], [14], thanks to its non-destructive principles and high resolution performance, which
255 3 might allow the survey of multiple areas without the need for uncovering the masonry and consequently the
456 5 investigation of extended portions that could lead to a more reliable and accurate assessment [15], [16], [17],
657 7 [18], [19]. GPR technique utilises high frequency electromagnetic waves reflections at boundaries between
858 9 materials exhibiting different electrical properties to determine the structure of the investigated area, which
10159 12 in the context of structures and buildings, typically includes voids, areas of wet material, and reinforcement
1360 14 structural element [20], [21], [22], [23]. Within these scopes, GPR has proven to be a highly effective and
1561 16 successful techniques, as reported in several reports and case studies [24], [25], [26], [27], [28].
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2063 The estimation of the mechanical properties of a masonry wall can be obtained by considering the behaviour
2122 of an ideal masonry wall and the mechanical properties of the constituent materials (stones, bricks, mortars,
2364 24 etc.), described by the following parameters [1], [29] [30]:
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2866 – Conservation state of bricks and mortar, in particular possible weathering effects and material
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- 3268 – Stone/brick dimension properties, with respect to the longer axis of each single element.
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- 3569 – Stone/brick shape, in particular concerning the associable morphology of the element (from pebbles
36 to perfectly cut stones) for each masonry leaf.
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- 3971 – Wall leaf connections, factors related to the presence of headers that might connect adjacent leaves.
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- 4272 – Horizontal bed joints characteristics, in particular their continuity.
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- 4573 – Vertical bed joint characteristics, in particular their staggering pattern.
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4874 By assigning a qualitative index to each of these factors, typically based on a fulfilled – not fulfilled scale, it
4975 is possible to calculate a numerical value representing the behaviour of the masonry that is correlated to its
505176 mechanical parameters (compressive strength, shear strength and modulus of elasticity). Despite being not
525377 completely exhaustive, such strategy has demonstrated its efficacy in providing a general overview of the
545578 masonry status which might help and assist the execution of experimental measurements targeting the
5679 materials mechanical properties.
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80 Although it is a promising subject, few GPR studies have targeted the masonry texture definition under this
1 operational perspective, revealing the difficulty inherent to this complex scenario [31], [32], [33].

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82 The deployment of GPR as a tool for the diagnosis of a structure, being this in terms of maintenance,
restoration or safety assessments, requires to accurately evaluate the internal construction and condition of
masonry, its geometrical morphology and composition, as well as the capability of determining the possible
coexistence of modern constructive elements with ancient masonry ones. The challenge is therefore to
precisely reconstruct the order and the alternation between bricks, determine their size and orientation, and
delineate the mortar joints distribution, all tasks that requires a high resolution definition of shallow objects
with limited size and potentially limited electromagnetic impedance contrast. Finally, it must be considered
that such assessment should be performed without excessively altering or damaging the surface, and
potentially from one side only.

81 These requirements necessarily imply the deployment of a survey platform optimised for the task, as it
should answer two main operational demands. First of all, the need for sufficient resolution to detect and
image elements within the first 2-5 centimetres, as well as to produce results as much informative and
readable as possible [34], [35], [36], [37]. This aspect is also a consequence of the well-known GPR
effectiveness dependency on the user ability to interpret the obtained images. Secondly, the necessity of
moving towards a three dimensional acquisition approach, due to the shallow depth of the targets of interest,
their limited size and the level of detail required for the subsurface characterisation [38], [39]. All these
aspects prevent the adoption of a sparse 2D profile approach, resulting in the necessity of collecting a 3D
data volume spatially compliant with the Nyquist spatial sampling criterion, in order to avoid aliasing during
data reconstruction [40].

83 Under this perspective, the aim of the following research is to determine the potential of GPR methodologies
in providing useful, i.e. quantitative and numerical, details related to the geometrical morphology of a
masonry wall, to a level such that the extracted information can be effectively employed for determining the
quality level of the masonry and to support the building assessment procedures, essential precondition for
bringing the GPR technique into practice for on-site investigations. For this reason, a portion of a wall with

106 known masonry architecture was surveyed with a high frequency GPR platform, making it possible to assess
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107 the reliability of the methodology with respect to the previously highlighted parameters.

108 The paper is organised as follows. Section 2 describes the carried out geophysical survey methodology and
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109 the survey strategy, while in Section 3 the obtained GPR results and the analysis of the reconstruction
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110 performance are presented and discussed. Finally, Section 5 integrates the obtained reconstruction in the
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111 evaluation of the masonry quality, and a summary of the findings and potential developments are briefly
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112 addressed in Section 6.

113 . SURVEY AREA AND METHODOLOGY

114 For the purpose of the study, a recently covered wall has been selected to evaluate the GPR potential in
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115 reconstructing the morphology of masonry buildings. The site has been chosen as it presents several critical
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116 aspects in terms of masonry design, constituent elements distribution, size and geometry, as can be seen in
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117 Fig 1.



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119 **Figure 1: Experimental area.**

120 From the photographs prior to the restructuring, it can be seen that the selected site is composed of three main
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121 areas: a first sector exhibiting a geometrically regular brickwork (marked A in Fig. 1) on top of a segmental
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122 arch (marked B in Fig. 1), i.e. an arch whose intrados is circular but less than a semicircle, a sign of a former
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123 aperture within the masonry wall, visible with its correspondent jack arch in the lower part of Fig. 1 (marked

124 C in Fig. 1). This represents the typical relieving arch design, built over a lintel or a jack arch to divert loads
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125 and hence relieving the lower member from excessive loading.

126 An area of 70-by100 cm has been surveyed (Fig. 2a), covering the first two previously described areas, as
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127 shown in Fig. 2b.



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229 **Figure 2: survey area details.**

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130 Within these (Fig. 2c), the portion of the upper area that has been acquired consists of 3 rows of bricks each of
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27 them including 5 to 6 elements, unevenly distributed, as well as inhomogeneous mortar joint thickness, while
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30 boundaries) with a maximum skewback angle of 35 degrees with respect to the arch keystone, and a core of
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133 brickwork between the underside of the arch and the top of the lintel.
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135 GPR data were acquired using an IDS Georadar TR-SHF radar, a ground coupled impulse system with a
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39 central frequency and a bandwidth of 3 GHz. The device carries two bow-tie antennas spaced 6 cm and
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41 oriented perpendicular to the survey line (Fig. 3a). The sensor head, which is essentially a passive component
427 weighting approximately 2 kg and with a size of 6 by 12 cm, is connected to a central unit responsible for the
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44 generation, transmission and reception of the signal. The required dense and regular 3D acquisition grid has
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139 been obtained by directly placing a cardboard variant of the PSG (Pad System for Georadar, [41]) over the
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140 wall (Fig. 3b), ensuring parallelism between adjacent profiles, while the inline sampling was controlled
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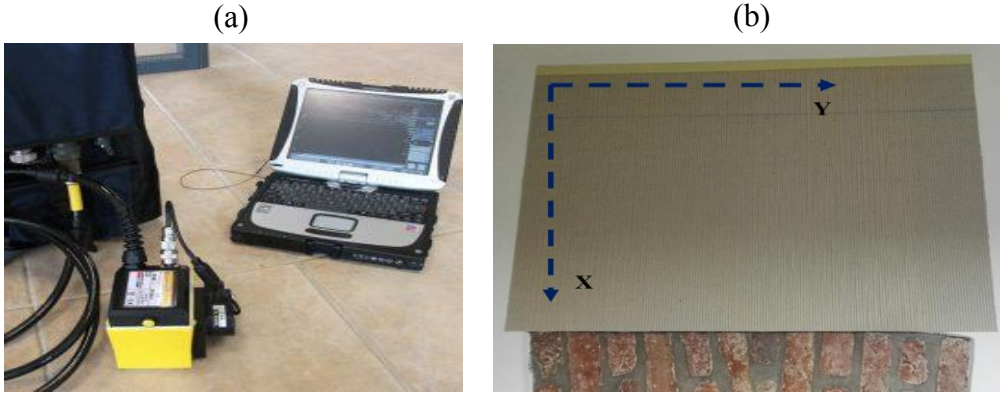


Figure 3: (a) employed GPR platform and (b) survey geometry.

In this case, data were acquired along the ceilings to the floor direction. However, as logistic constraints might necessitate different acquisition geometries compared to the chosen one, two orthogonal volumes have been acquired to assess eventual differences in the imaging results. The choice of the orthogonal direction derived from the fact that, despite not expected to exhibit a strong polarimetric response, the regular geometry of a brickwork, particularly the vertical and horizontal mortar joints, might impact the magnitude of the scattering response [42]. Moreover, in case of structural metallic reinforcement elements such scheme will ensure a full detection, as a consequence of the well-known sensitivity to polarisation of highly conductive linear targets [43]. Precise correspondence among the acquired samples has been ensured by rotating the system with respect to the reflection centre of the antennas, while maintaining the same acquisition geometry.

Acquisition parameters are provided in Table I. For each volume, a total of 150 profiles have been acquired, with an acquisition time of approximately 60 minutes.

Table I: acquisition parameters.

Parameter	Value
Inline sampling	0.4 cm
Crossline sampling	0.7 cm
Time sampling	0.039 ns
Time window	20 ns
Antenna separation	6 cm
Antenna height	< 1 cm
Antenna frequency	3 GHz

System bandwidth	3 GHz
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Considering the resolution performance and consequently the capability of correctly recognising the bricks layer, as a general rule two events can be distinguished if the targets are separated in time by a time difference at least equal to half of the envelope width. The emitted waveform of the employed GPR system exhibits a -3 dB envelope width of approximately 0.14 ns, resulting in a required time difference between the top and the bottom of each layer of 0.14 ns in order to be separated. Considering that the dielectric constant of typical plaster used in masonry lies within the 3-5 range, even considering a velocity of 17 cm/ns, i.e. the less favourable conditions, the spectral characteristics of the system allows for a proper separation between the plaster layer, which has a thickness of 3 cm, and the upper faces of the brickwork, as the temporal extension of the plaster covering is approximately 0.17 ns.

As mentioned in the previous section, although in some cases it might be easier to detect subsurface features from raw GPR data, migration represents one of the most useful tool to facilitate a correct interpretation and geometrical reconstruction of the subsurface features. Therefore, the results of the experimentation are presented both in term of raw time slice, obtained by applying a time calibration and a linear frequency filtering to remove out of band noise, and a set of depth slices, retrieved via Kirchhoff migration. Details on the processing algorithms are provided in Table II.

Table II: data processing details.

Processing step	Description
Time calibration	Time shift.
Trace alignment	Correlation window.
Frequency filtering	Zero-phase Butterworth filter. Frequency range 1 – 4 GHz.
Velocity analysis	Hyperbola fitting. Mean aperture: 5 cm.
3D migration	2D-2step approach.

As a result of the velocity analysis, providing a velocity of approximately 15 cm/ns, the vertical resolution limit can be set at approximately 1.25 cm considering the central frequency of 3 GHz, once again demonstrating the background separation ability.

179 **2 . GPR RESULTS**

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The following section presents the obtained GPR results, for both raw/processed data and horizontal/vertical antenna orientation. To quantitatively assess the detection accuracy and reconstruction performance, the following aspects have been evaluated: for the raw data, the detection performance, defined as the comparison between the number of identifiable elements within the time slice ensemble and the actual one. In addition to this, the migrated data have been assessed also considering the reconstruction accuracy, determined as the evaluation of the estimated element size and the actual one. Such decision has been taken considering that the resolution along the crossline direction in unfocussed data depicts low resolution features owing to the long tails of the diffraction hyperbola, hence the factual size and location of the scattering element is typically erroneous.

2.1 Unmigrated time slices

Unmigrated time slices produced by the horizontal configuration, i.e. with the dipoles perpendicular to the survey direction, are presented in Fig 5.

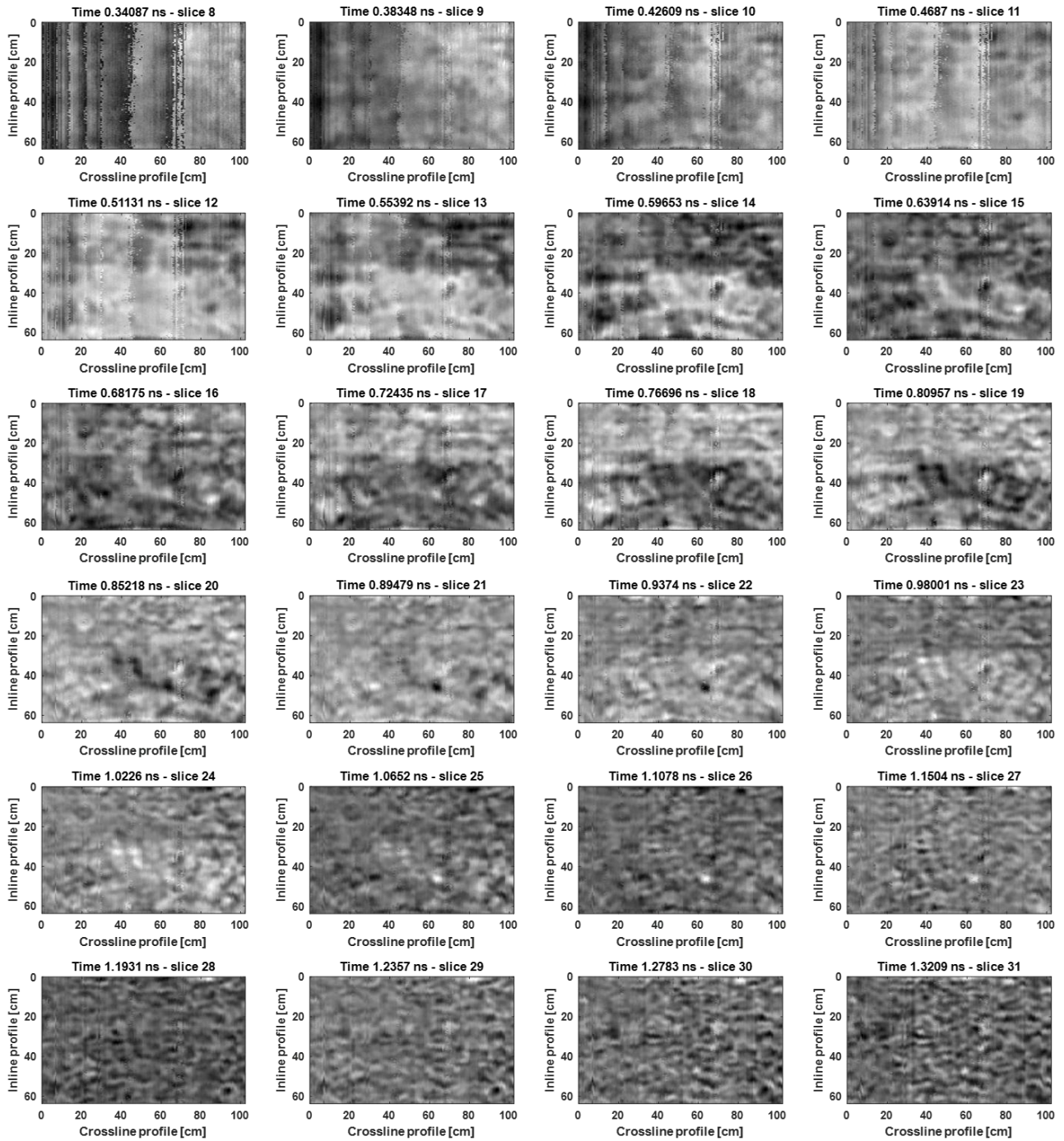
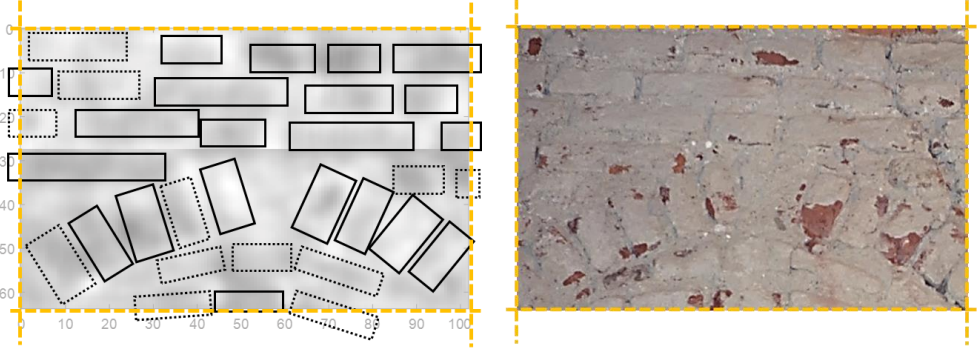


Figure 5: GPR results, unmigrated horizontally oriented time slices.

From the analysis of the slices ensemble, the two different morphologies previously highlighted can be identified. In particular, the intrados and the extrados of the segmented arch are evident (particularly from slice 13 to slice 20 of Fig. 5) in the lower part of the slice (inline direction interval from 30 cm onward), spanning the entire crossline dimension, while the geometrically regular brickwork can be delineated within the area above. The scattering contribution from the masonry can be assumed to start from the eleventh slice after the background reflection, corresponding to a time interval of 0.46 ns and resulting in an estimated

200 plaster thickness of approximately 3.5 cm, which is closely resembling the existent value. Both the areas
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 201 exhibit a similar temporal extension, lasting for roughly 20 slices and consequently resulting in an estimated
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 202 layer thickness of 0.8 ns, which leads to a thickness of 12 cm. Finally, mortar joints can be easily delineated,
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 203 and in particular the horizontal bed ones, as a consequence of the orientation of the antenna pattern, which
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 204 can better image the horizontal mortar lines compared to the vertical ones.

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 1205 It is therefore possible to extract some quantitative information on the geometrical composition of the
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 1206 masonry, even if it is clear that the actual number of bricks would be difficult to determine. This remark
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 1207 applies to the relieving arch as well, for which the contour can be accurately delineated, but several
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 1208 uncertainties remain when attempting to enumerate each voussoir. Carefully analysing the set slice by slice,
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 2109 it is possible to determine a quantitative indication of the level of fidelity that can be obtained under the
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 2210 perspective of defining the geometrical texture of the wall. In particular, in each slice the potential presence
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 2211 of a masonry element has been highlighted to obtain the final texture map provided in Fig. 6, along with the
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 2712 actual status.



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 4314 **Figure 6: Reconstruction performance, unmigrated horizontally oriented time slices.**



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 4515 The achieved detection capability, generated by approximately 8 to 10 slices and relying to a certain extent
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 4716 on the user interpretation ability, is numerically described in Table 3.

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 5117 **Table III: Numerical reconstruction performance, unmigrated horizontally oriented time slices.**

	Investigated area	Investigated sector	Estimated number of elements	Actual number of elements
	Upper area	First row	4	5

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		Second row	4	5
		Third row	4	5
	Lower area	Relieving arch	7	9
		Brickwork core	2	9

To assess the effects of a change in the survey direction, the same set of slices is presented for the orthogonally oriented acquisition, i.e. vertical configuration (Fig. 7).

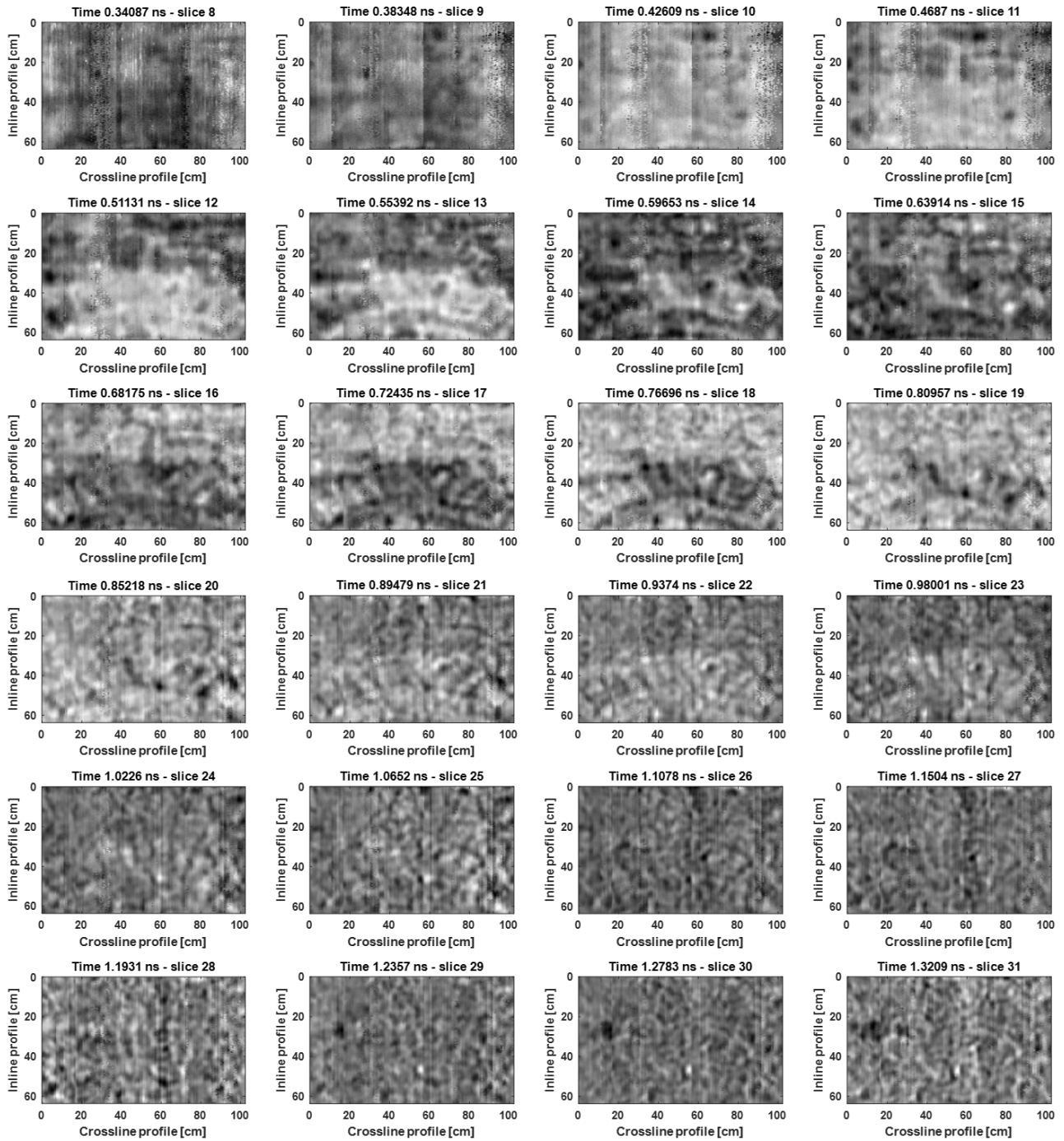
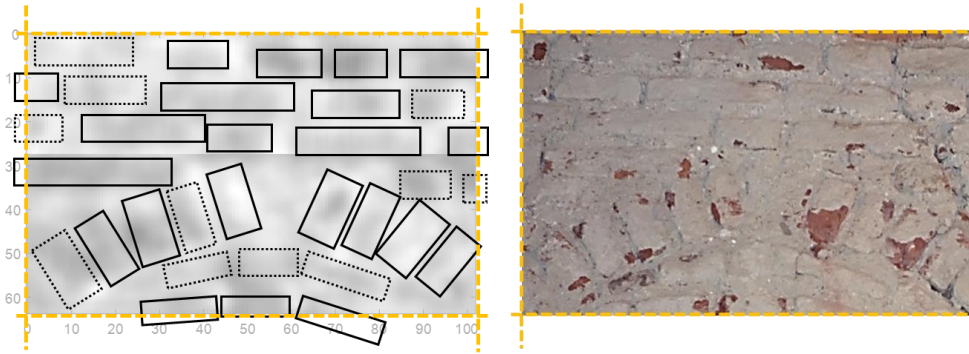


Figure 7: GPR results, unmigrated vertically oriented time slices.

As a first strand of the analysis, it can be seen that, compared to Fig.6, there are no noticeable differences in the imaging performance, as also changing the survey direction still manages to highlight the two masonry areas previously described. A comparable similarity exists also with respect to the amplitudes distribution of the two ensembles, both presented with the same dynamic range for a proper comparison.



However, from a deeper analysis, it emerges that the vertical mortar joints are better imaged, as expected from the previous considerations on the antenna pattern geometry, and consequently the reconstruction of the

229 elements exhibiting a limited height turns out to be facilitated, as shown in Fig. 8 and numerically described
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 230 in Table IV.



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 18 **Figure 8: Reconstruction performance, unigrated vertically oriented time slices.**

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 21 **Table IV: Numerical reconstruction performance, unigrated vertically oriented time slices.**

	Investigated area	Investigated sector	Estimated number of elements	Actual number of elements
	Upper area	First row	4	5
		Second row	3	5
		Third row	4	5
	Lower area	Relieving arch	7	9
		Brickwork core	4	9

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 235 What can be achieved, in this case through the interpretation of a slightly lower number of slices (6 to 8
 236 approximately) is still a partial reconstruction, as the advantages in determining the vertical discontinuities is
 237 balanced by the limited readability of the image. Concerning the segmented arch, no significant
 238 discrepancies exist with the orthogonal correspondent, in terms of both imaging readability and level of
 239 information that gathers. The comparison between the two schemes demonstrates that, although some

240 differences can be appreciated, no significant advantages exist in choosing a specific acquisition direction,
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241 meaning that such aspect does not represent a critical parameter when planning the survey.

242 Summarising what can be extract from the presented results, it can be concluded that unmigrated data,
243 although providing acceptable and satisfactory results, allows mostly for a qualitative interpretation, as only
244 the appearance of the investigated area can be characterised and retrieved, but a complete reconstruction is
245 still out of reach. While missing the elements close to the boundaries of the acquisition pad represents a
246 solvable issue when approaching the survey on a larger scale, several bricks are not detectable regardless
247 their size or geometry.

248 **2.2 Migrated depth slices**

249 To solve the challenge of quantitatively reconstruct the masonry wall, i.e. determine the number and actual
250 location of each element, migrated data are presented for each acquisition scheme, starting from the
251 horizontally oriented volume (Fig. 9). As described in Table II, a limited aperture value has been selected to
252 further improve the resolution of the produced images and to avoid the introduction of processing artefacts.

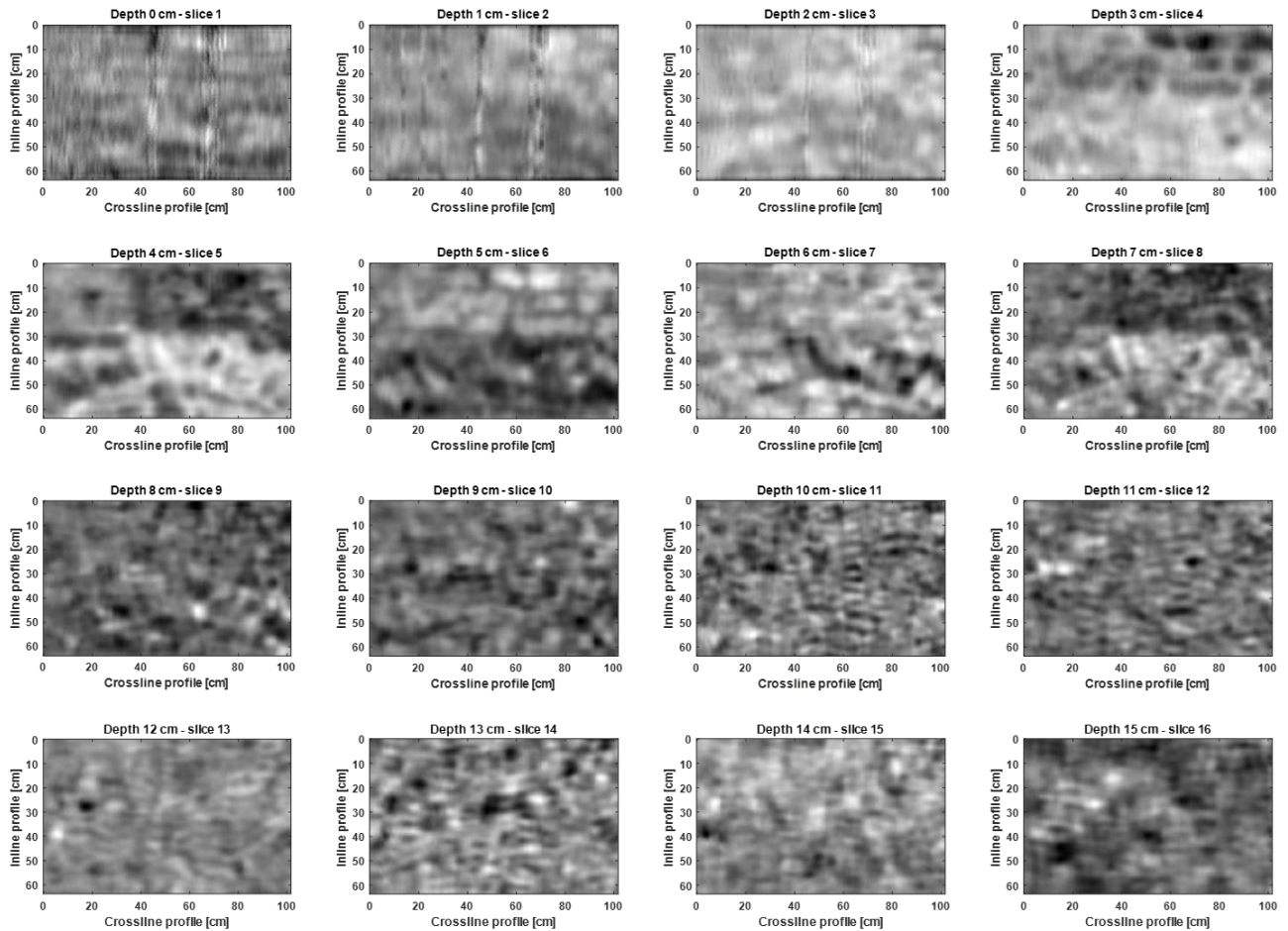
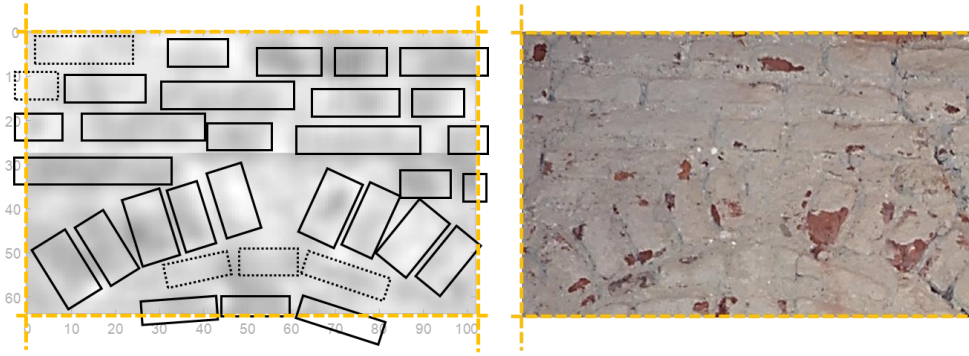


Figure 9: GPR results, migrated horizontally oriented depth slices.

As expected, the additional processing step has the benefit of accurately reconstructing each scattering element and the relative boundaries, at the same time sharpening the image, as can be clearly seen in the depth slices ensemble. In agreement with the predicted plaster thickness and brick thickness, masonry layer appears at a depth of 3 cm, and its scattering contributions vanishes with depths greater than 11 cm. What can be also noticed is that the signature of the arch appears slightly deeper, meaning either a locally increased covering thickness or an underestimated velocity value. The close correspondence with the existent masonry texture is particularly evident for the geometrically regular brickwork (slice 4 in Fig. 9).

The additional advantage of analysing migrated data over unmigrated ones is that it requires a significantly reduced number of radar slices to properly reconstruct the masonry morphology, 2 to 3 images, thus mitigating as well the effects of the user familiarity in interpreting the data. Detection performance are sketched in Fig. 10.

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Figure 10: Reconstruction performance, migrated horizontally oriented depth slices.

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As before, Table V describes the quantitative results in terms of detected masonry elements with respect to

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the existent ones.

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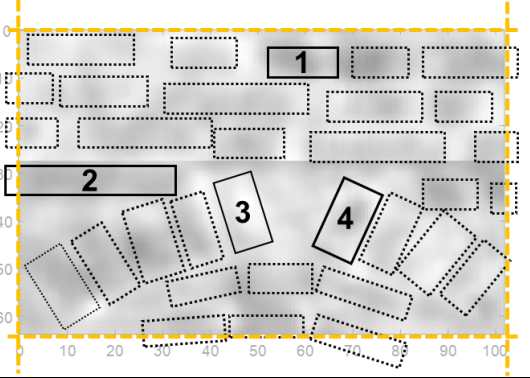
Table V: Numerical reconstruction performance, migrated horizontally oriented depth slices.

	Investigated area	Investigated sector	Estimated number of elements	Actual number of elements
	Upper area	First row	4	5
		Second row	4	5
		Third row	5	5
	Lower area	Relieving arch	9	9
		Brickwork core	6	9

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The texture is clearly identifiable, and the actual number of elements and their size can be guessed, with a remarkable level of accuracy and detail. Only the smallest and less regularly organised elements still represent a challenge, even if their presence can be supposed considering the texture of the surrounding neighbourhood. As a figure of merit, Table VI describes the obtained accuracy in determining the size of brick examples compared to the actual values.

277 **Table VI: Numerical reconstruction accuracy, migrated horizontally oriented depth slices.**

Brick example	Element label	Estimated size	Actual size
	1	Height: 7.5 cm Length: 14 cm	Height: 6.5 cm Length: 14 cm
	2	Height: 6 cm Length: 30 cm	Height: 5 cm Length: 27 cm
	3	Height: 12 cm Length: 7 cm	Height: 12 cm Length: 6 cm
	4	Height: 13 cm Length: 7 cm	Height: 12 cm Length: 6.5 cm

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279 Given the spatial uncertainty given by the system resolution, it is evident the close match between the
280 retrieved data and the factual one, even for bricks with limited size, as for the case of element labelled 1 in
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282 Table VI.

283 From the results, it is evident that a number of parameters and features that can be used for evaluating the
284 quality of the masonry can be extracted, including the disposition of the vertical joints, their offset to the
285 normal direction, the horizontal continuity and regularity, and the proper adjacency between vertical and
286 horizontal elements.

287 To complete the evaluation, the migrated depth slices acquired with the vertical configuration are presented
288 in Fig. 11.

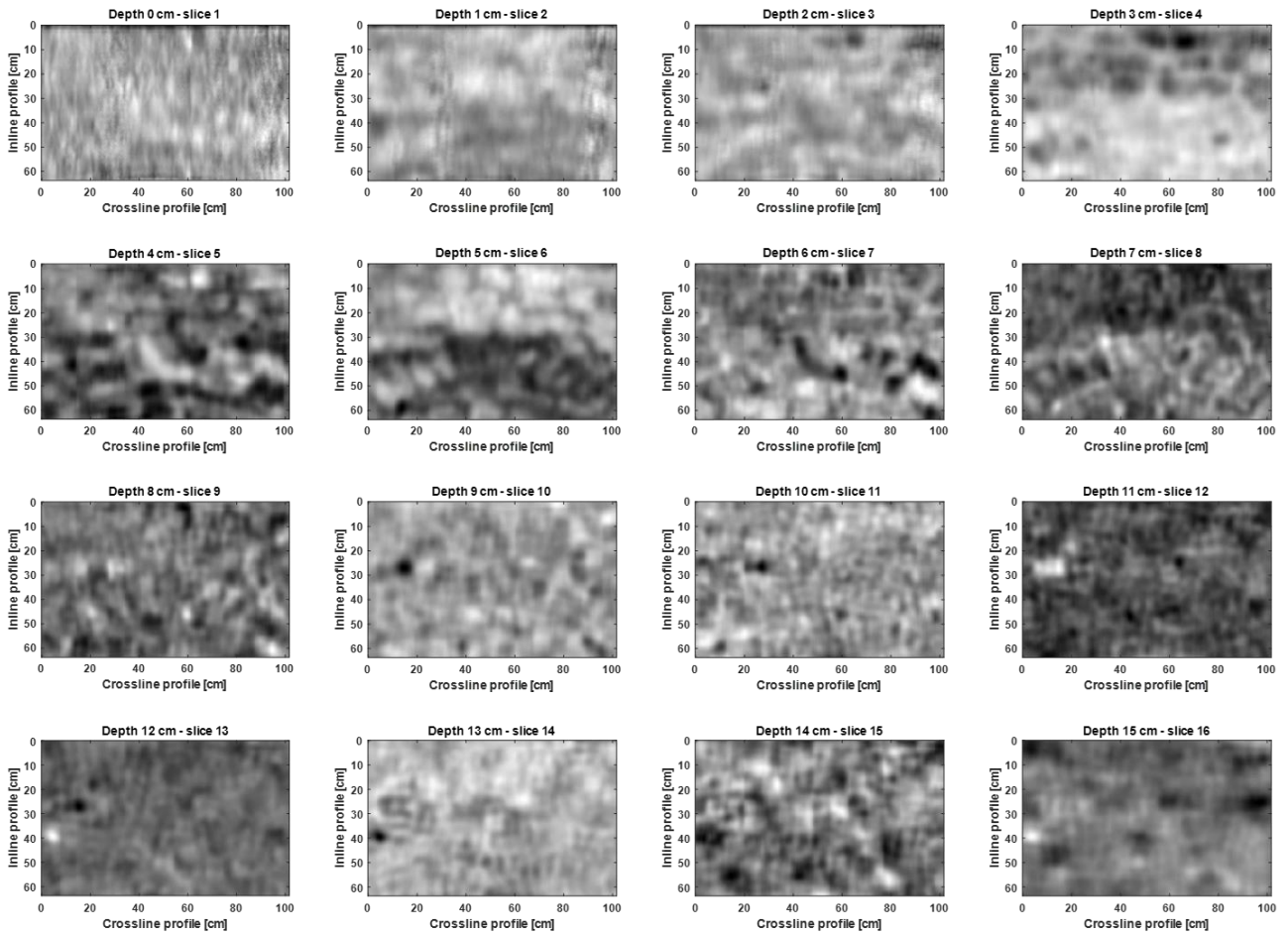
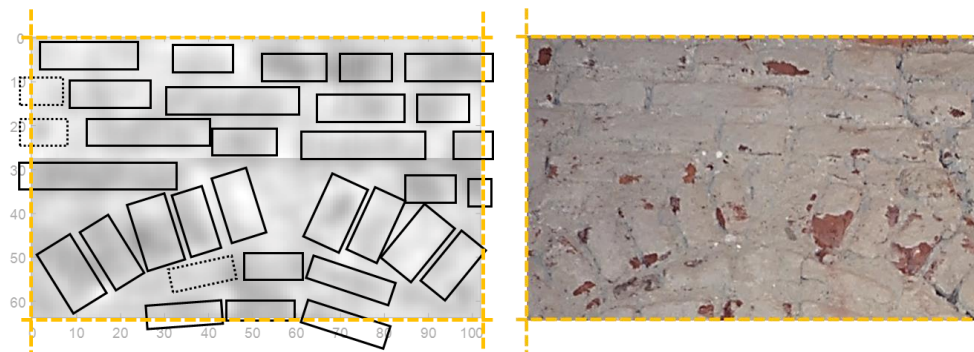


Figure 11: GPR results, migrated vertically oriented depth slices.



A very similar level of detection and reconstruction performance can be defined, following what has been commented from the analysis of Fig 9. The better delineation of vertical elements that emerged from the analysis of the unmigrated data results in a clearer definition of the brickwork core under the arch, as assessed in Fig. 12 and Table VII, respectively. The geometrical characterisation from the vertically oriented acquisition required approximately 2 to 3 slices, in agreement with the values obtained from the horizontal one.



297 **Figure 12: Reconstruction performance, migrated vertically oriented depth slices.**

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Table VII: Numerical reconstruction performance, migrated vertically oriented depth slices.

	Investigated area	Investigated sector	Estimated number of elements	Actual number of elements
	Upper area	First row	5	5
		Second row	4	5
		Third row	5	5
	Lower area	Relieving arch	9	9
		Brickwork core	8	9

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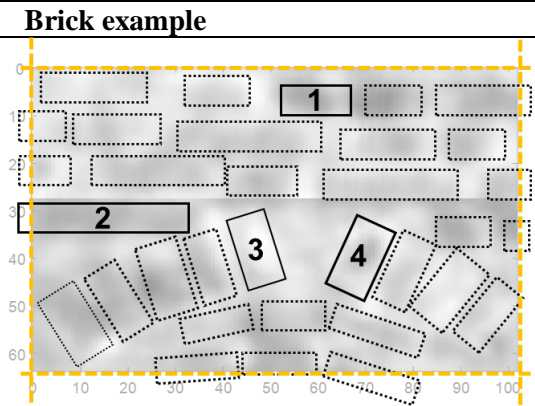
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Except for these evidences, the process of summing the scattering energy within the limited aperture and collapsing it at the apex of the relative diffraction have the effects of reducing the differences due to the acquisition direction, which are even less noticeable. Results of the reconstruction accuracy evaluation are provided in Table VIII.

304 **Table VIII: Numerical reconstruction accuracy, migrated vertically oriented depth slices.**

Brick example	Element label	Estimated size	Actual size
	1	Height: 6 cm Length: 13 cm	Height: 6.5 cm Length: 14 cm
	2	Height: 6 cm Length: 29 cm	Height: 5 cm Length: 27 cm
	3	Height: 14 cm Length: 6 cm	Height: 12 cm Length: 6 cm
	4	Height: 11.5 cm Length: 6 cm	Height: 12 cm Length: 6.5 cm

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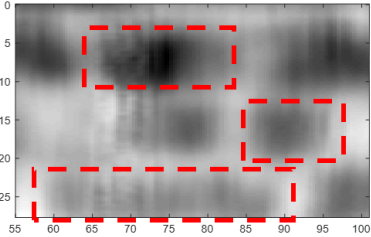
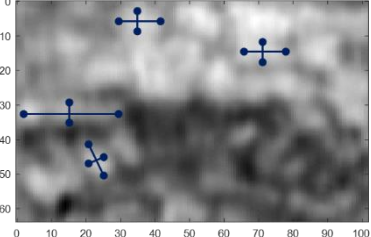
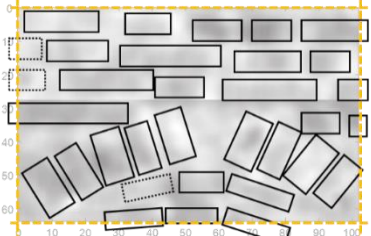
306 To summarise, despite the increased processing weight required to produce the focussed results, the
 1 migration procedure has proved to be a crucial processing step to achieve a correct final interpretation,
 307 capable of providing valuable information for determining the characteristics and the morphology of a
 3 capable of providing valuable information for determining the characteristics and the morphology of a
 308 masonry wall. The analysis of the depth slices has shown that each element can be accurately located and its
 5 size estimated, all features that are involved, directly or not, in the structural assessment process.
 309 size estimated, all features that are involved, directly or not, in the structural assessment process.
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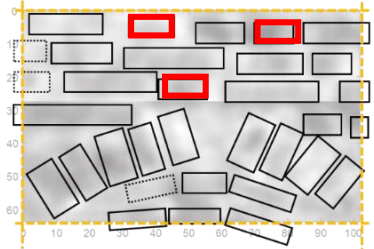
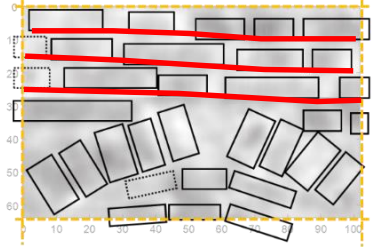
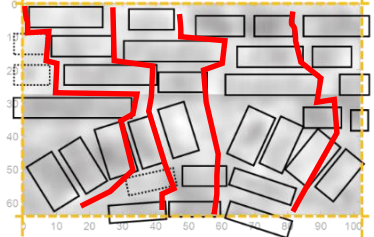
311 5 – MASONRY QUALITY ESTIMATION

312 From the outcomes summarised in Figure 12 and Table VIII, it is possible to confidently index and label the
 14 parameters described in the introduction section, and in particular it can be stated that they are almost all
 15 fulfilled (conservation state, constituents dimension and shape, horizontal joint characteristics) or at worst, as
 16 a consequence of the remaining uncertainties, partially fulfilled (vertical joints characteristics, wall leaf
 17 connection).
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26 This means that the surveyed area can be categorised with a high masonry quality index, and consequently a
 27 good behaviour of masonry related to both horizontal and vertical actions. Table XI describes these concepts.
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31 **Table IX: Masonry quality estimation results.**
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Quality parameter	Assessment	Index	GPR evidence
Conservation state of bricks and mortar and appraisable mechanical properties	Apparently in good state.	Fulfilled	
Stone/brick dimension properties	Accurately determined (examples in Table VIII). Bed: 12-14 cm Header: 6-7.5 cm Stretcher: 25-34 cm	Fulfilled	
Stone/brick shape	Brickwork predominant, no evidences of stonework.	Fulfilled	

<p>1 2 3 4 5 6 7 8</p> <p>Wall leaf connections</p>	<p>Presence of possible headers.</p>	<p>Partially fulfilled</p>	
<p>9 10 11 12 13 14 15 16</p> <p>Horizontal bed joints characteristics</p>	<p>Continuous horizontal bed joints.</p>	<p>Fulfilled</p>	
<p>17 18 19 20 21 22 23 24 25</p> <p>Vertical bed joint characteristics</p>	<p>Partially staggered vertical joints.</p>	<p>Partially fulfilled</p>	

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Commenting on these performances, the lower level of quality estimated for the vertical mortar lines is a result of the limited extension of such features and considering also the resolution, and hence the spatial ambiguity, achieved by the adopted GPR system. However, it can be also seen that the missing an element, in this particular case the brick under the arch, does not actually invalidate the approach, as (1) the characterisation of such parameter can still be confidently computed thanks to the obtained knowledge of the surrounding areas, and (2) the presence or absence of the brickwork has a limited impact on the masonry strength, as it is completely sustained by the overlying arch, considering also that the structural element is completely and correctly reconstructed. Regarding the headers between masonry leaves, and therefore the possibility of being in the presence of a multiple leaves masonry structure, the estimation relies in the first instance on the geometrical aspect of the brickwork, i.e. an element is defined as a candidate header based on the appearing size. Finally, the positive index on the condition state of the masonry constituents arises from the absence in the GPR slices of visible voids or significant erosion phenomena degrading the accuracy in elements delineation.

334 It can be therefore affirmed that the GPR survey methodology advanced in this article has demonstrated its
 335 capability in properly retrieving the majority of the required parameters needed for a quantitative masonry
 336 quality assessment, with a high level of confidence and without impacting on the wall surface at all.

337 Applying the methodology described in (Borri et. al. 2015a and 2015b), the investigated masonry appears to
 338 be characterised by a compressive strength (f_m) of approximately $600 N/cm^2$, a shear strength (τ_0) of 9
 339 N/cm^2 , a shear modulus (G) of $640 N/cm^2$ and a modulus of elasticity (E , overestimated by the
 340 methodology) of $2300 N/cm^2$. Such values represent a masonry exhibiting a high carrying capacity of
 341 horizontal in- and out-of-plane actions, as well as a satisfactory resistance to the vertical ones.

342 As a comparison, in case the distinguishing parameters were totally fulfilling the quality requirements, the
 343 masonry strength would be enhanced of a 10 percent factor in contrasting the horizontal actions, while the
 344 shear properties would gain a 30 percent increase. Conversely, if we assume no information on the presence
 345 of headers, a decrease of the parameters defining the masonry quality can be estimated in a 16 – 20 percent
 346 range, mainly as a consequence of the contraction in the out-of-plane horizontal actions resistance. As well,
 347 the inability of adequately delineating the vertical bed joints causes an additional reduction of the parameters
 348 up to a 30 percent, or even higher (as for the shear strength value computation). In this case, such contraction
 349 is a consequence of the decreasing of the masonry resistance also to in-plane horizontal actions.

350 Table X details the commented performance.

351 **Table X: Estimated masonry response comparison.**

Masonry evidences	Compression strength (f_m)	Shear strength (τ_0)	Shear modulus (G)	Modulus of elasticity (E)
Ideal masonry characterisation	$670 N/cm^2$	$13 N/cm^2$	$900 N/cm^2$	$2500 N/cm^2$
From GPR survey (Table XI)	$600 N/cm^2$	$9 N/cm^2$	$640 N/cm^2$	$2300 N/cm^2$
No information on headers	$480 N/cm^2$	$7 N/cm^2$	$540 N/cm^2$	$1950 N/cm^2$
No delineation of vertical bed joints	$425 N/cm^2$	$5.7 N/cm^2$	$455 N/cm^2$	$1780 N/cm^2$

353 In summary, the Table once again underlines the significance of determining the presence of headers and the
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354 role of the vertical joints delineation for a proper structural assessment, features that can both be adequately
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355 addressed through a high frequency, 3D GPR investigation.
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356 In conclusion, this study has revealed that the proposed methodology might become an operationally suitable
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357 tool to investigate a masonry structure and to provide preliminary qualitative and quantitative information on
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358 its potential behaviour to both horizontal and vertical actions. In addition, it should be considered also the
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1359 well-known capability of the GPR technique of detecting wooden and metallic elements within the structure,
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1360 which allows the designer to additionally understand the quality of the performed modifications or
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1361 interventions and the residual resistance level.
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362 **6 – CONCLUSIONS**

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243 Within the context of the condition assessment of masonry walls for seismic behaviour characterisation, and
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264 generally for structure inspection and diagnosis, this study has demonstrated the successful application of
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265 GPR technique in retrieving essential information on the masonry typology and the geometrical properties of
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366 its constituent elements (brick, stone and mortar) properties, a knowledge that is typically achieved through
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367 the use of more invasive approach and consequently with a limited scalability. In particular, the aim was to
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368 evaluate the performance of the methodology in determining the presence, the partial presence, or the
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369 absence of specific construction features that could provide a quantitative indication of the quality of the
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4070 masonry.
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4371 Therefore, the challenges addressed are associated not only with the detection of shallow targets with limited
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4572 size and potentially a similar dielectric behaviour, but also with their precise reconstruction, accurately
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473 enough to allow for the extraction of the masonry quality parameters, a set of attributes which includes
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374 among others the delineation of the mortar joint and the constituent elements dimensions. These scopes have
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375 required the deployment of a dedicated 3D, high frequency GPR platform.
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5376 Results have been obtained for both unmigrated and focussed GPR slices, as well as acquired along different
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5377 survey directions, and their analysis has highlighted that unmigrated data only provide a qualitative
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5978 characterisation of the surveyed area, adequate for determining typology and texture morphology, but the
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379 achieved performance in terms of single element reconstruction are limited. On the contrary, the migration
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380 algorithm has the effect of improving the readability of the produced images, thus consequently reducing the
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381 influence of the user confidence in interpreting the data, and allows for an encouraging recognition and
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382 geometrical reconstruction of all the elements composing the masonry, retrieving almost the entire set of
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383 parameters needed for the masonry quality assessment.
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384 Research remains to exploit some important aspects, first of all a clearer and improved identification of the
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385 number of headers, considering its importance in determining the wall capacity to resist seismic actions (as
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386 highlighted in Table X). This can be done by acquiring a correspondent area on the other side of the wall,
387 considering that a properly connected multi-leaf connection requires elements traversing the entire wall
388 structure, and hence location matches between potential header candidates can expectedly identify the
389 fulfilment of such structural property. Another aspect requiring attention for a deeper seismic behaviour
390 characterisation is the identification of tothing, i.e. the process of constructing the temporary end of a wall
391 with the end stretcher of every alternate course projecting, at the wall-to-tie-column interface, either being at
392 an interior or at corner, as well as tothing at cross walls intersections. Such confinement technique ensures a
393 satisfactory bond between adjacent structural elements, controlling the out-of-plane behaviour and therefore
394 improving the building robustness and ductility against seismic forces.

395 From an engineering perspective, future works will be focussed on the automation of the detection,
396 recognition and identification process through the development of dedicated image processing algorithms, so
397 that the reliance upon the user interpretation ability can be further reduced and the system performance
398 improved. Another advancement that can be put forward is the conceptualisation of a flexible, wide-scale
399 survey equipment for an efficient and productive application on site, seamlessly integrating the sensor and
400 the positioning equipment.

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404 **References**

- 405 [1] Borri A., Corradi M., Castori G. and De Maria A. (2015). A method for the analysis and classification of
406 historic masonry. *Bulletin of Earthquake Engineering*, 13, 2647-2665. doi: 10.1007/s10518-015-9731-4

- 407 [2] Borri A., Castori G., and Corradi M. (2015). Determination of Shear Strength of Masonry Panels
408 Through Different Tests. *International Journal of Architectural Heritage*. 9(8), 913- 927. doi:
409 10.1080/15583058.2013.804607
410
- 411 [3] Lagomarsino S., and Podestà S. (2004) Seismic vulnerability of ancient churches: II. Statistical analysis
412 of surveyed data and methods for risk analysis. *Earthquake Spectra*, 20(2), 395–412. doi:
413 10.1193/1.1737736
414
- 415 [4] Lourenço P.B., Mendesa N., Ramosa L.F., Oliveira D.V. (2011) Analysis of masonry structures without
416 box behavior. *International Journal of Architectural Heritage*, 5 (4–5), 369–382. doi:
417 10.1080/15583058.2010.528824
418
- 419 [5] Zuccaro, G., Cacace, F. (2015) Seismic vulnerability assessment based on typological characteristics.
420 The first level procedure "SAVE", *Soil Dynamics and Earthquake Engineering*, 69, 262-269. doi:
421 10.1016/j.soildyn.2014.11.003
422
- 423 [6] Taffarel, S., Caliman, M., Valluzzi, M.R., Modena, C. (2016). Seismic vulnerability assessment of
424 clustered historical centers: Fragility curves based on local collapse mechanisms analyses. In 16th
425 International Brick and Block Masonry Conference, Trends, Innovations and Challenges, Padua, Italy,
426 June 2016; 2463 – 2470. doi: 10.1201/b21889-322
427
- 428 [7] Perelli, F.L.de Gregorio, D.,Cacace, F. and Zuccaro, G. (2019) Empirical vulnerability curves for Italian
429 masonry buildings, In 7th International Conference on Computational Methods in Structural Dynamics
430 and Earthquake Engineering, Crete; Greece; June 2019, 1745-1758, doi: 10.7712/120119.7033.19864
431
- 432 [8] Borri, A., De Maria, A., Casaglia S. (2014). The EAL-M method for the seismic classification of the
433 existing masonry buildings: a comparison between different methods and preliminary evaluations of
434 other typologies. (in Italian) *Progettazione Sismica*, 5(2), 11-29, 10.7414/PS.5.2.11-29.
435
- 436 [9] Erberik, A.M. (2008) Generation of fragility curves for Turkish masonry buildings considering in-plane
437 failure modes. *Earthquake Engineering Structural Dynamics*, 37(3): 387–405. 10.1002/eqe.760.
438
- 439 [10] Rota M., Penna, A., Magenes G. (2010). A methodology for deriving analytical fragility curves for
440 masonry buildings based on stochastic nonlinear analyses. *Engineering Structures*, 32(5), 1312-1323,
441 10.1016/j.engstruct.2010.01.009.
442
- 443 [11] Pagnini, L.C., Vicente, R., Lagomarsino, S., Varum, H. (2011). A mechanical model for the seismic
444 vulnerability assessment of old masonry buildings. *Earthquakes and Structures*, 2(1), 25-42.
445 10.12989/eas.2011.2.1.025
446
- 447 [12] Garavaglia E., Anzani A., Maroldi F., Vanerio F. (2020) Non-Invasive Identification of Vulnerability
448 Elements in Existing Buildings and Their Visualization in the BIM Model for Better Project
449 Management: The Case Study of Cuccagna Farmhouse. *Applied Sciences*, 10(6), 2119,
450 10.3390/app10062119
451
452
453
454
455
456
457
458
459
460
461
462
463
464
465

- 441 [13] Benedetto, A., Pajewski, L. (Eds.). (2015). Civil engineering applications of ground penetrating radar.
442 Springer. doi: 10.1007/978-3-319-04813-0
443
- 443 [14] Daniels, D.J. Ground Penetrating Radar, 2nd ed.; The Institution of Electrical Engineers: London, UK,
444 2004; 565 doi: 10.1002/0471654507.eme152
445
- 445 [15] Barraca, N., Almeida, M., Varum, H., & Matias, M. S. (2014). The use of GPR in the rehabilitation of
446 built heritage. In Near Surface Geoscience 2014-20th European Meeting of Environmental and
447 Engineering Geophysics, Athens, Greece, September 2014, 1-5. doi: 10.3997/2214-4609.20141998.
448
- 448 [16] De Donno, G., Di Giambattista, L., & Orlando, L. (2017). High-resolution investigation of masonry
449 samples through GPR and electrical resistivity tomography. *Construction and Building Materials*, 154,
450 1234-1249. doi: 10.1016/j.conbuildmat.2017.06.112
451
- 451 [17] Lai, W. W. L., Derobert, X., & Annan, P. (2018). A review of Ground Penetrating Radar application in
452 civil engineering: A 30-year journey from Locating and Testing to Imaging and Diagnosis. *NDT & E*
453 *International*, 96, 58-78. doi: 10.1016/j.ndteint.2017.04.002
454
- 454 [18] Martini, R., Carvalho, J., Barraca, N., Arêde, A., & Varum, H. (2017). Advances on the use of non-
455 destructive techniques for mechanical characterization of stone masonry: GPR and sonic tests. *Procedia*
456 *Structural Integrity*, 5, 1108-1115. doi: 10.1016/j.prostr.2017.07.096.
457
- 457 [19] McCann, D. M., & Forde, M. C. (2001). Review of NDT methods in the assessment of concrete and
458 masonry structures. *Ndt & E International*, 34(2), 71-84. doi: 10.1016/S0963-8695(00)00032-3.
459
- 459 [20] Angiulli, G., Barrile, V., Cacciola, M. The GPR technology on the seismic damageability assessment of
460 reinforced concrete building. In 2005 Progress in Electromagnetics Research Symposium, Hangzhou,
461 China, August 2005, 1(3), 303-307. doi: 978-193307707-9
462
- 462 [21] Diamanti, N., Giannopoulos, A., & Forde, M. C. (2008). Numerical modelling and experimental
463 verification of GPR to investigate ring separation in brick masonry arch bridges. *NDT & E International*,
464 41(5), 354-363. doi: 10.1016/j.ndteint.2008.01.006
465
- 465 [22] Solla, M., Lorenzo, H., Rial, F. I., Novo, A. (2012). Ground-penetrating radar for the structural
466 evaluation of masonry bridges: Results and interpretational tools. *Construction and Building Materials*,
467 29, 458-465. doi: 10.1016/j.conbuildmat.2011.10.001
468
- 468 [23] Tosti, F., Ferrante, C. Using Ground Penetrating Radar Methods to Investigate Reinforced Concrete
469 Structures. *Surv Geophys* 41, 485–530 (2020). doi: 10.1007/s10712-019-09565-5
470
- 470 [24] Barrile, V., & Pucinotti, R. (2005). Application of radar technology to reinforced concrete structures: a
471 case study. *NDT & E International*, 38(7), 596-604. doi: 10.1016/j.ndteint.2005.02.003
472
- 472 [25] Binda, L., Zanzi, L., Lualdi, M., & Condoleo, P. (2005). The use of georadar to assess damage to a
473 masonry Bell Tower in Cremona, Italy. *NDT & E International*, 38(3), 171-179. doi:
474 10.1016/j.ndteint.2004.03.010
475

- 475 [26] Catapano, I.; Ludeno, G.; Soldovieri, F.; Tosti, F.; Padeletti, G. Structural Assessment via Ground
476 Penetrating Radar at the Consoli Palace of Gubbio (Italy). *Remote Sensing*, 10(1), 45. doi:
477 10.3390/rs10010045.
478
- 478 [27] Perez-Gracia, V., Santos-Assuncao, S., Caselles, O., Clapés, J., & Canas, J. A. (2014). Study of wood
479 beams in buildings with ground penetrating radar. In 15th International Conference on Ground
480 Penetrating Radar, June 2014, Brussels, Belgium, 31-35. doi: 10.1109/ICGPR.2014.6970379.
481
- 481 [28] Santos-Assunção, S., Perez-Gracia, V., Caselles, O., Clapes, J., & Salinas, V. (2014). Assessment of
482 complex masonry structures with GPR compared to other non-destructive testing studies. *Remote*
483 *Sensing*, 6(9), 8220-8237. doi: 10.3390/rs6098220
484
- 484 [29] Binda L., Saisi A. and Tiraboschi C. (2000). Investigation procedures for the diagnosis of historic
485 masonries. *Construction and Building Material*, 14, 199–233. doi: 10.1016/S0950-0618(00)00018-0
486
- 486 [30] Borri, A., De Maria, (2015). Masonry Quality Index (MQI): correlation with the mechanical
487 characteristics and knowledge levels (in Italian). *Progettazione Sismica*, 6(3), 45-63, 10.7414/PS.6.3.45-
488 63.
489
- 489 [31] Colla, C., Fernández, A. J., Garanzini, S., & Marelli, M. (2010). Diagnostic by imaging: 3D GPR
490 investigation of brick masonry and post-tensioned concrete. In 13th International Conference on Ground
491 Penetrating Radar, Lecce, Italy, August 2012, 1-7. doi: 10.1109/ICGPR.2010.5550175
492
- 492 [32] Hamrouche, R., Klysz, G., Balayssac, J. P., Rhazi, J., Ballivy, G. (2012). Numerical simulations and
493 laboratory tests to explore the potential of Ground-Penetrating Radar (GPR) in detecting unfilled joints
494 in brick masonry structures. *International Journal of Architectural Heritage*, 6(6), 648-664. doi:
495 10.1080/15583058.2011.597484
496
- 496 [33] Pérez-Gracia, V., Solla, M. (2015). Inspection procedures for effective GPR surveying of buildings. In
497 *Civil Engineering Applications of Ground Penetrating Radar*, Springer, Cham. 97-123, doi: 10.1007/978-
498 3-319-04813-0_4
499
- 499 [34] Negri, S., & Aiello, M. A. (2020). High-resolution GPR survey for masonry wall diagnostics. *Journal of*
500 *Building Engineering*, 33, 1-11, doi: 101817. 10.1016/j.jobee.2020.101817
501
- 501 [35] Lombardi, F., Griffiths, H. D., Lualdi, M., & Balleri, A. (2020). Characterization of the Internal
502 Structure of Landmines Using Ground-Penetrating Radar. *IEEE Geoscience and Remote Sensing*
503 *Letters*. Early Access, doi: 10.1109/LGRS.2020.2970249
504
- 504 [36] Luo, T. X., Lai, W. W., Chang, R. K., & Goodman, D. (2019). GPR imaging criteria. *Journal of Applied*
505 *Geophysics*, 165, 37-48. doi: 10.1016/j.jappgeo.2019.04.008
506
- 506 [37] Pieraccini, M., Miccinesi, L. (2018). No-contact GPR for investigating painted walls. In 2018 17th
507 International Conference on Ground Penetrating Radar, Rapperswil, Switzerland, June 2018, 1-6. doi:
508 10.1109/ICGPR.2018.8441580
509
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547
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555
556
557
558
559
560
561
562
563
564
565

- 509 [38] Pomfret, J. (2006). Ground- penetrating radar profile spacing and orientation for subsurface resolution
510 of linear features. *Archaeological Prospection*, 13(2), 151-153. doi: 10.1002/arp.285
- 511 [39] Samet, R., Çelik, E., Tural, S., Şengönül, E., Özkan, M., & Damcı, E. (2017). Using interpolation
512 techniques to determine the optimal profile interval in ground-penetrating radar applications. *Journal of*
513 *Applied Geophysics*, 140, 154-167. doi: 10.1016/j.jappgeo.2017.04.003
- 514 [40] Lombardi, F., Griffiths, H. D., & Lualdi, M. (2018). Sparse Ground Penetrating Radar Acquisition:
515 Implication for Buried Landmine Localization and Reconstruction. *IEEE Geoscience and Remote*
516 *Sensing Letters*, 16(3), 362-366. doi: 10.1109/LGRS.2018.2872357
- 517 [41] Lualdi, M. (2011). “True” 3D Acquisition using GPR Over Small Areas: A Cost Effective Solution. In
518 24rd EEGS Symposium on the Application of Geophysics to Engineering and Environmental Problems,
519 Charleston, USA, April 2011, 541-550. doi: 10.3997/2214-4609-pdb.247.21
- 520 [42] Pieraccini, M., Pisaneschi, M., Noferini, L., & Atzeni, C. (2007). Polarimetric radar signature of
521 masonry walls. *NDT & E International*, 40(4), 271-274. doi: 10.1016/j.ndteint.2006.11.004.
- 522 [43] Lualdi, M., Lombardi, F. (2014). Significance of GPR polarisation for improving target detection and
523 characterisation, *Nondestructive Testing and Evaluation*, 29 (4), 345-356. doi:
524 10.1080/10589759.2014.949708