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# Advanced non-destructive techniques for the diagnosis of historic buildings: the Loka-Hteik-Pan temple in Bagan

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## Abstract

The archaeological site of Old Bagan, located in the centre of Myanmar, is one of the most remarkable and ancient Asian site with over three thousand monuments, scattered in an area of about eighty square kilometers. The site was hit in 2016 by the last of a series of earthquakes. The Loka-Hteik-Pan is a hollow-core temple featured by a small elegant curvilinear tower. It was significantly damaged by the event, losing the upper part of the tower, as many other temples of the area. Emergencies like seismic events generally require quick responses and targeted solutions. When a built area is involved, damaged buildings need structural assessments with a special focus on space and time occupancy, without compromising the reliability of the results. A workflow for data acquisition and analysis is proposed, using non-destructive techniques to evaluate the materials performances and measure spatial changes over times. Deformation analysis is performed on LiDAR data, acquired prior and after the earthquake, with the goal of measuring small changes occurred in the wall surfaces. The preliminary results of the tests are presented with the purpose to provide a knowledge base, useful to guide the interventions for preserving the monument and its heritage.

*Keywords:* Cultural heritage; Non-Destructive Testing; Terrestrial Laser Scanning; Point Cloud; Deformation Analysis;

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## 1. Introduction

Tangible cultural heritage like architectural and archaeological ones are a testimony of cultural values, shared by people during a period of time, which need to be preserved in order to be passed down to future generations. Such values are carried not only by the appearance of the object but also by the integrity of all its components [1]. The documentation process is a multidisciplinary activity

involving a broad range of sciences among which geomatics is essential to relate and integrate all the sparse information pieces in a comprehensive description of the whole building system [2]. Non-Destructive Testing (NDT) is a broad collection of methods for the examination and analysis of objects and systems without impairing them or affecting their integrity. They are widely used in civil engineering for testing the performances of new structures as well for the damage monitoring in old constructions. Such techniques include the sonic transmission method, used to test the elastic properties in order to acquire information about the structural performance of the materials and guide future interventions on the building. Nowadays geomatics methods like topography and photogrammetry also allow a contactless non-invasive acquisition of metric information from

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28 objects. Light Detection and Ranging (LiDAR) 75  
29 is a promising topographic technique which has 76  
30 been extensively used for structural monitoring. 77  
31 Its main advantage is the possibility to acquire 78  
32 automatically and massively high detailed mea- 79  
33 sures from objects. Later the development in 80  
34 electronics reduced significantly the size and cost 81  
35 of such sensors, while developments of algorithms 82  
36 for spatial analysis and manipulation automated 83  
37 the possibility to extract useful information from 84  
38 the acquired data. These advancement boosted 85  
39 the application of such technique to a larger set 86  
40 of purposes such as deformation detection and 87  
41 measurement, potentially reducing the cost of 88  
42 human intervention[3]. 89  
43

## 44 2. Research aim

45 The presented research was conducted in 2018  
46 as a collaboration between Carleton University,  
47 Mandalay Technological University and the De-  
48 partment of Archaeology and National Museums  
49 of Myanmar. It involved a series of field activities,  
50 workshops and conferences aimed to disseminate  
51 the knowledge about Bagan archaeological site by  
52 using innovative techniques for the documentation  
53 and conservation of its cultural values. The site  
54 includes thousands of religious buildings and was  
55 affected by a series of seismic events over time,  
56 the last of them in 2016. The object of study is  
57 one of the temple which has been studied over  
58 time and was damaged by the last earthquake  
59 which destroyed the upper part of the roof. The  
60 goal of this research is to show the effectiveness of  
61 advanced non-destructive techniques that can be  
62 deployed after an earthquake for a fast and reliable  
63 assessment of seismic damages and guidance for  
64 the interventions to be put in place.  
65

## 66 3. Diagnostic techniques

### 67 3.1. Non-destructive testing

68 One of the older and simpler systems for  
69 evaluating the structural health of a building is  
70 the direct visual inspection, which requires the  
71 physical access to all the building parts and it  
72 is strongly influenced by subjectivity[4]. On  
73 the other hand, non-destructive techniques allow  
74 to measure physical properties of the materials

75 which are crucial to determine the building seismic  
76 response. One of these techniques is sonic pulse  
77 velocity testing, which can be used to estimate  
78 the elastic properties of materials. This type of  
79 test is based on the propagation of waves inside  
80 the materials caused by an impulsive force. The  
81 velocity and the time spent to receive the signal,  
82 generated from the waves, can be read between  
83 the thickness of the internal and external surfaces  
84 of the walls (direct sonic tests) or along the same  
85 surface (indirect tests) at a specific distance. While  
86 visual inspection gives a general overview of the  
87 observed state of damage along the structure, the  
88 sonic tests are performed with the goal of evalu-  
89 ating the elastic properties through the reading  
90 of the velocity waves. Depicting the variation of  
91 velocity in different locations of the temple may  
92 correspond to an increase or decrease of the elastic  
93 properties due to internal cracks, deteriorations  
94 and/or detachments.  
95

### 96 3.2. Point cloud processing

#### 97 Registration

98 LiDAR is a ranging technology for automatically  
99 and randomly extracting massive amount of mea-  
100 sures from objects, resulting in a dense collection  
101 of points called point cloud. After filtering out  
102 systematic errors and outliers, point clouds can  
103 be considered as an highly detailed sample of a  
104 spatial feature, with a certain amount of random  
105 error called noise. Commonly point cloud noise  
106 is calculated as roughness, which is the deviation  
107 from a local plane. The accuracy of the sample is  
108 commonly given as spatial density or point spacing.  
109 When surveying a 3-dimensional feature multiple  
110 scans of the same scene need to be acquired and  
111 consequently aligned together. This process, called  
112 registration, is the computation of the fixed-scale  
113 geometric transformation, necessary to reference  
114 multiple scans in the same Coordinate Reference  
115 System (CRS). It can be done either by using a  
116 different reference system, independently defined  
117 by a set of Ground Control Points (GCPs), or  
118 using the same CRS of one of the scan positions.  
119 The latter, known as co-registration, does not  
120 require additional sensory while an high overlap  
121 between the scans is necessary to avoid systematic  
122 errors [5].

123 Pre-determined associations between features from  
124 the two sets can be used for computing the pa-  
125 rameters of the transformation. In this approach,

126 called target-based registration, markers are used  
127 as tie points for the scans registration. In the  
128 cloud to cloud approach no prior knowledge about  
129 correspondences is given, these are automatically  
130 found using points coordinates minimizing the  
131 reciprocal distances between the clouds. Intensive  
132 distance computations on point clouds are im-  
133 proved using indexing structures like the octree [6],  
134 which is an efficient hierarchical data structure  
135 based on a regular space decomposition<sup>1</sup>. A very  
136 popular algorithm for the cloud to cloud fine  
137 registration is the Iterative Closest Point (ICP) [7].  
138 This algorithm selects a set of samples from one  
139 cloud and find point to point correspondences to  
140 neighbours in the other set. The point to point  
141 calculation method requires an high degree of  
142 overlap between the pairs and an uniform point  
143 density within the scans.  
144

#### 145 *Spatial analysis and interpolation*

146 Development of algorithms for the analysis of  
147 spatial changes increased the effectiveness of us-  
148 ing LiDAR techniques and potentially extended  
149 their application field for detecting and measuring  
150 spatio-temporal changes without any prior knowl-  
151 edge. Deformation analysis and change detection  
152 are the two main specialization of this topic, the for-  
153 mer dealing with the binary problem of distinguish  
154 stable and unstable areas while the latter is focused  
155 on the accurate measurement of small changes, usu-  
156 ally close to the instrument tolerance. Change  
157 detection techniques are usually applied to geo-  
158 sciences problems, where the co-registration of laser  
159 scans acquired in different epochs on the base of  
160 manually identified stable areas can be a challenge.  
161 Automatic co-registration of laser scans and change  
162 detection are indeed mutually dependent: registra-  
163 tion of scans affected by spatial changes requires  
164 robustness against outliers (unstable areas), that is  
165 the sampling of tie points only from stable areas.  
166 This issue is addressed either using sequential [8]  
167 and combinatory approaches [9]. Identification of  
168 stable areas where to sample tie points for the laser  
169 scans registration is usually less problematic when  
170 the application field involves buildings, whose 3D

171 models are usually featured by parametrized sur-  
172 faces. In the construction field deformation is usu-  
173 ally computed as a deviation of the acquired data  
174 from geometric primitives and out-of-plane tests are  
175 also common to check the deflection of wall surfaces  
176 from vertical [10] [11].

177 One of the first cloud comparison method devel-  
178 oped was the cloud to model (or mesh) (C2M) [12]  
179 which can be used to compare point sets to sur-  
180 faces models. Surface reconstruction from unstruc-  
181 tured point clouds is performed by interpolating  
182 the points, usually with patches resulting in a facet  
183 model called mesh. While several approaches exist  
184 to find the best surface fitting for a point set,  
185 uncertainties introduced by interpolation are diffi-  
186 cult to quantify. Methods for the cloud to cloud  
187 (C2C) comparison have also been developed, com-  
188 puting distances along normal directions without  
189 performing a surface reconstruction of the whole  
190 point set, but rather approximating locally the sur-  
191 face. Least squares planes, Delaunay triangulations  
192 and quadric surfaces are some of the models used as  
193 local best approximation of a point set, depending  
194 on the roughness and the level of detail [13]. Brodu  
195 and Lague proposed a C2C method called Model  
196 to Model Multiscale Cloud Comparison (M3C2) [14]  
197 which addresses some of the limitations of the other  
198 C2C approaches. First of all the algorithm com-  
199 putes normals for the whole point cloud to be com-  
200 pared at different scales, choosing the surface fit-  
201 ting which minimizes the difference in normal ori-  
202 entation between neighbour points. Thereafter the  
203 normals direction is used to project the neighbour  
204 points, whose mean value represents the average  
205 position of the points along that direction, while  
206 the standard deviation measures the roughness of  
207 the sampled points. Cloud to cloud local distance  
208 is thus computed as the distance between the two  
209 mean values. The SD is calculated for both the  
210 clouds and the results, together with the registra-  
211 tion error (if available), are used to estimate the un-  
212 certainty of each measured distance, giving a local  
213 level of confidence for the C2C comparison. A sta-  
214 tistical method for determining significant changes  
215 with the C2M method has also been proposed and  
216 used to test C2M against M3C2 [9]. M3C2 method  
217 has been tested in remote sensing [15] and close-  
218 range applications [16] with positive results. De-  
219 tection and measurement of changes between two  
220 (or more) point sets acquired in different times re-  
221 quires the two sets to be registered using in the  
222 same Coordinate Reference System (CRS). The po-

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<sup>1</sup>Given a point set and a the smallest cubical bounding box containing it, the space within the box is divided recursively into 8 sub-cubes at each octree depth level till no points are contained or a minimum density level is reached.

223 tential presence of changes between the two sets 272  
224 poses the problem to exclude this bias from the 273  
225 computation of registration parameters. Automatic 274  
226 registration methods like ICP, which extract ran- 275  
227 domly tie points to be used for adjustment, can 276  
228 lead to misalignment if the deformation area is too 277  
229 large [13]. Most of the cited methods consider only 278  
230 displacements in one dimension, usually coincident 279  
231 with the normal vector. Registration methods like 280  
232 the Least Square 3D (LS3D) [17] have been used in 281  
233 geosciences applications for measuring deformation 282  
234 in the 3D space [18], given a prior knowledge about 283  
235 the areas subjected to change. 284

## 237 4. Data acquisition and analysis

### 238 4.1. Description of the temple and main interven- 239 tions

240 The Loka-Hteik-Pan temple, numbered as 1580 292  
241 by Pichard’s Inventory [19], is a middle-size tem- 293  
242 ple, built in 1113 A.D. in the south-western part 294  
243 of the old Bagan site (Myanmar). This temple is 295  
244 still nowadays one of the most remarkable example 296  
245 of Burmese and Buddhist Architecture, not only for 297  
246 its shape and function, but also because of the orig- 298  
247 inal paintings of Buddha’s Life which are located on 299  
248 the inner surfaces of the temple. 300

249 The temple is an isolated structure of about  $150\text{ m}^2$ , 301  
250 made of fired bricks, which can be divided into 302  
251 three spaces: the main chamber, which hosts the 303  
252 Buddha’s statue, the antechamber and the en- 304  
253 trance (Figure:1). The entrance and the antecham- 305  
254 ber are covered by two barrel vaults, while the 306  
255 main chamber hosts a cloister vault [21]. Shapes 307  
256 are massive and articulated by the sequence of sev- 308  
257 eral terraces up to the level of the Śikhara, a sort 309  
258 of curvilinear high tower characteristic of Indian 310  
259 and Burmese temples. The terraces are accessi- 311  
260 ble via an internal and narrow staircase, dug in 312  
261 the thickness of external wall (more than 2.5 m). 313  
262 The Śikhara (Figure:1) is one architectural element 314  
263 with origin in the Indian architecture - it is a sort 315  
264 of curvilinear tower which offers a slender appearance 316  
265 to the temple [22]. 317

266 Three perforated brick windows let some light enter 318  
267 into the main chamber and they are the unique way 319  
268 to light the interior. From the exterior, the windows 320  
269 are framed by ornamental portals, with character- 321  
270 istic details of the Buddhist art. The North façade 322  
271 has the entrance and it is marked by a portal, which

presents a tympanum. Most of the external surfaces  
were covered by stucco carvings, applied directly  
on the outer layer of the masonry, mouldings sculp-  
tures or reliefs. Nowadays, only partial remaining  
parts of these carvings are still located on the sur-  
faces.

From the 13th and 19th centuries, Loka-Hteik-Pan  
temple passed through several construction phases  
that are not well known.

Due to the numerous seismic events, which hit Cen-  
tral Myanmar during 20<sup>th</sup> and 21<sup>th</sup> centuries (See  
Figure 2), Loka-Hteik-Pan temple, as well as many  
other Bagan temples, underwent several structural  
and non-structural interventions. The most sig-  
nificant changes occurred after Bagan earthquake  
(1975), when locals funded heavy strengthening  
projects [23]. According to Pichard [19], “a rein-  
forced concrete belt at the top of the walls” was in-  
serted along the perimeter walls of the main cham-  
bers. This description does not represent the entire  
intervention that was made: three beams made of  
reinforced concrete, not continuous, were located  
at each corners of the main chamber and of the an-  
te-chamber along the height of the structure. This  
work was supposed to be done in order to re-  
establish the connection between the walls.

Many portions of the portals and all the final parts  
of the pinnacles were rebuilt during the last cen-  
tury, using modern and industrial fired bricks. The  
Śikhara was restored several times and nowadays  
many of its bricks are not original, but newer and  
pasted through the use of cement based mortar.  
The original spire of the Śikhara disappeared; this  
element was repositioned with a new steel fastener  
after 1975 Earthquake, but it collapsed during the  
Chauk earthquake (2016). The spire was not re-  
placed after this event and the highest part of the  
Śikhara, which did not collapse, was restored with  
the insertion of new bricks.

The frescoes were treated the first time in 1993, af-  
ter the earthquake that hit Bagan in 1992. The  
paintings were cleaned against the action of the  
dust, using mechanical brushes and wet cleaning  
technique with chemical solvents. The last inter-  
vention on the mural paintings took place in 2015:  
liquid grout injection was employed to re-establish  
the adhesion of them on the walls.

### 319 4.2. Damage survey

320 The damage survey was evaluated through vi-  
321 sual inspection in May 2018, aiming at updating  
322 the evaluation of the damage after the 2016 Chauk

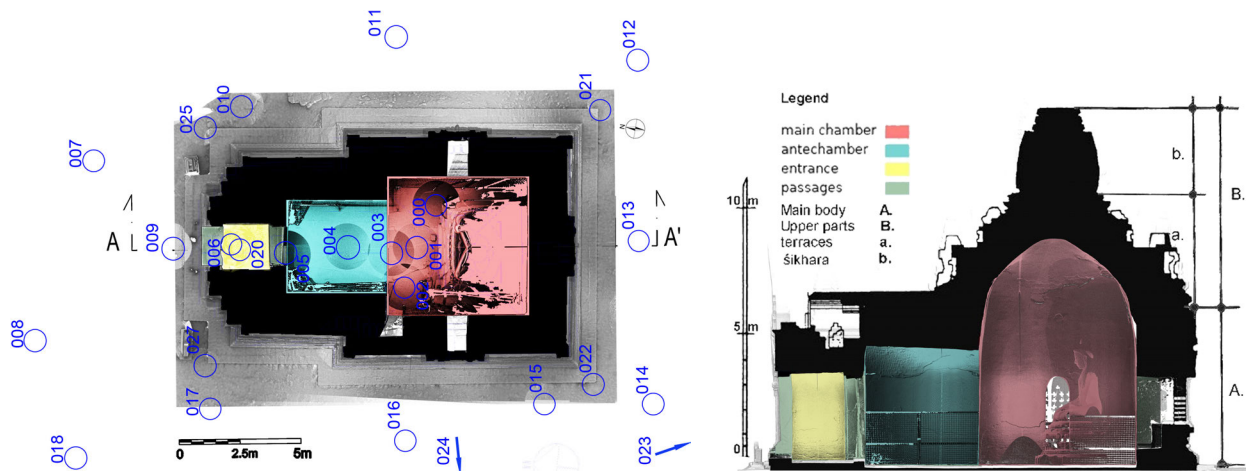


Figure 1: Loka-Hteik-Pan: vertical section and ground level plan with the scan locations from 2018. Source: updated from [19]

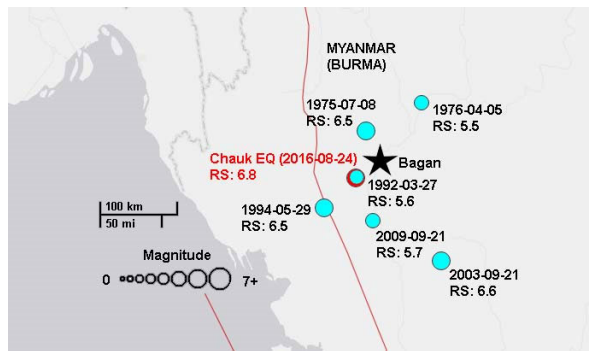


Figure 2: Location of the last strong seismic events (1975 – 2016). RS=Richter scale [20].

323 Earthquake. Loka temple presents moderate dam-  
 324 age at the connection between the two orthogonal  
 325 walls of the South-East corner, highlighted by two  
 326 vertical cracks from both the sides. In general, this  
 327 part suffers more damage than the other portions  
 328 of the monument and presents also a generalized  
 329 detachment of the corner along the entire height of  
 330 the temple. It is important to underline that this  
 331 damage located at South-East corner was already  
 332 noticed by Pichard [19] after Bagan Earthquake in  
 333 1975 and was yet present before the application of  
 334 reinforced concrete beams. In other parts of the  
 335 structure, there are many minor and medium cracks  
 336 along the boundaries between beams and masonry  
 337 surfaces. This kind of openings can be associated  
 338 to the incompatibility of the two materials in terms  
 339 of stiffness, strength and thermal effects. The tym-

340 panum of the North façade is visibly affected by  
 341 out-of-plane deformations and some parts of this  
 342 element have been reattached more recently, by using  
 cement based mortar (Fig 3). Due to the orienta-

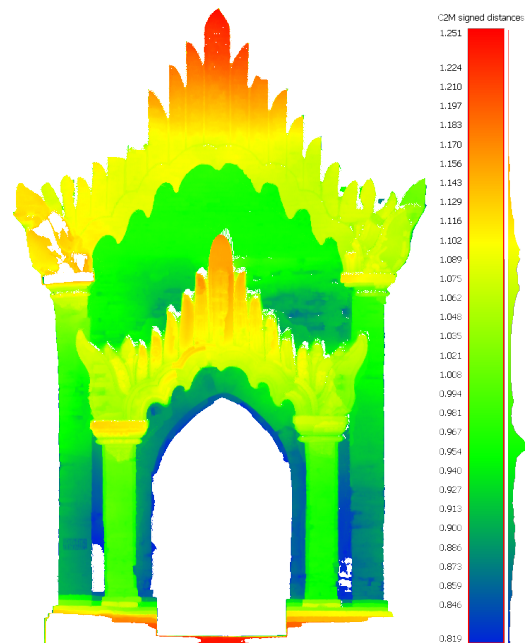


Figure 3: Out-of-plane deformations on the front façade tympanum. C2M distances are computed from a vertical plane fitted on the horizontal profile of the façade.

343 tion of the bricks on the vaulted systems, both in  
 344 the antechamber and the entrance, there is a lon-  
 345 gitudinal crack along the length of the vaults. As  
 346

347 previously referred, the temple was covered by carvings 367  
 348 and stuccoes, which nowadays suffer of heavy 368  
 349 decay and damage. All the structure is affected 369  
 350 by partial and sometimes complete detachment of 370  
 351 the plaster. Moreover, due to the weathering, the 371  
 352 original mud mortar disappeared and this caused a 372  
 353 widespread disconnection of the brick units. Figure 373  
 354 8 shows the damage pattern of the South façade ac-  
 355 cording to the ICOMOS-ISCS 2008 procedures [24].  
 356 The current state of damage have been drawn on  
 357 the ortho-projection of the coloured point clouds  
 358 from the 2016 and 2018 surveys.

### 359 4.3. Sonic tests

Indirect sonic tests were carried out along all the  
 external surface of the walls, at different heights,  
 on surfaces composed both by original and mod-  
 ern bricks. Direct sonic tests were performed only  
 close the North façade of the temple, because the  
 cross section of the walls in this location is visi-  
 ble and accessible. The sonic tests were performed  
 in-situ during the technical visit in May 2018, us-  
 ing an impulse hammer PCB, a piezoelectric ac-  
 celerometer PCB ( $\pm 0.5g$ ) and an acquisition board  
 NI USB 4431. The tests were repeated more than  
 30 times per each location (17 locations of measure-  
 ment along the structure) to give statistical stabili-  
 ty to the results. From the Equation 1, Young’s  
 modulus ( $E$ ) can be estimated as function of the  
 density of the material ( $\rho = 1777 kg/m^3$ ) [21], Pois-  
 son’s ratio ( $\nu = 0.2$ ) and the velocity of the waves  
 ( $VP = 280 - 310 m/s$ ) [25].

$$E = \frac{\rho V_p^2 (1 + \nu)(1 - 2\nu)}{(1 - \nu)} \quad (1)$$

### 360 4.4. LiDAR survey

361 Two different metric surveys of the temple 364  
 362 were performed using a Terrestrial Laser Scanner 365  
 363 (TLS)<sup>2</sup> 3: in the 2016, before the Chauk earthquake 366  
 364 and in 2018, after the event. In 2018 a small tra- 367  
 365 verse was established in the area of the temple. 368  
 366 Traversing was essential for aligning the exteriors 369

<sup>2</sup>TLS is a subset of the LiDAR technology targeted to  
 building surveying. Their range is within some meters to  
 few hundreds of meters and they are also usually equipped  
 with a low-res camera whose pictures are used for colouring  
 the point cloud

<sup>3</sup>A FARO Focus 3D X330 was used, with an angular accu-  
 racy of 19", a ranging error (tolerance) of  $\pm 2mm$  and noise  
 between 0.3 and 0.4 mm.

and interiors point cloud and for checking, with a  
 different technique, the errors in laser scans regis-  
 tration. The position of the benchmarks was indeed  
 set in order to measure a set of natural features and  
 targets on the building exteriors and interiors to be  
 used as GCPs<sup>4</sup>. Table 1 shows the residuals on the  
 benchmarks coordinates<sup>5</sup>.

The LiDAR surveys performed in 2016 and 2018

Station point	X (mm)	Y (mm)	Z (mm)
2000	0	0	0
4000	0	2	9
1000	2	3	11
3000	2	3	11
5000	5	1	13

Table 1: Traverse residuals on the benchmark coordinates.  
 2000 was set as the origin of the system.

374 covered all the exterior façades and the interiors 375  
 376 of the temple. Figure 1 shows the position of the 377  
 378 scans of the 2018 survey: a loop scheme was set for 379  
 379 the exteriors while the scans from the interiors fol- 380  
 380 low linear sequence, from the antechamber to the 381  
 381 main room. A similar approach was used for the 382  
 382 2016 survey. Figure 4 shows the point spacing of 383  
 383 the registered point clouds, computed with Mesh- 384  
 384 lab [26] as the average distance from each point to 385  
 385 his neighbours. Datasets from 2018 survey are a bit 386  
 386 denser, especially regarding the exteriors, because 387  
 387 the number of scan was doubled from 9 scans in 388  
 388 2016 to 18 scans in 2018, while for the interiors the 389  
 389 number was almost the same (6 scans in 2016 and 7 390  
 390 in 2018). The sparser dataset (2016 exteriors) has 391  
 391 95% of the samples with a point spacing between 392  
 392 2 and 8 mm. Figure 5 shows that, apart from the 393  
 393 small differences within the surveys, uncertainty de- 394  
 394 riving from point clouds roughness is below 8 mm 395  
 395 for 95% of the sampled data in the worst scenario 396  
 396 (2016 exteriors). These point cloud statistics show 397  
 397 a potential tolerance of the metric information be- 398  
 398 ing extracted from the data in line with the goal to 399  
 399 detect spatial changes of 1 cm size (or bigger). 9- 400  
 Point clouds were re-sampled in order to reduce the  
 point cloud density. Points closer one to each other

<sup>4</sup>A Leica TS11 Total Station (TS) was used, with an an-  
 gular accuracy of 3" and a distance accuracy of 1 mm +  
 1.5 ppm with standard prism and 2 mm + 2 ppm reflector-  
 less.

<sup>5</sup>Traverse adjustment were performed with the Least  
 Squares (LS) method using the Microsurvey Starnet soft-  
 ware.

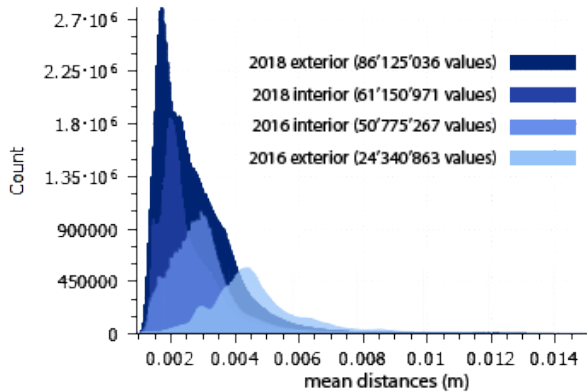


Figure 4: Point clouds densities. X axis show the average distances between points ( $m$ ) and Y axis the values count (number of points for each point spacing value).

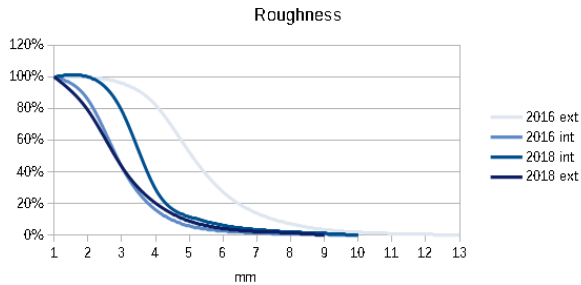


Figure 5: Point clouds roughness. X axis shows the distances and Y axis the percentage of points with that roughness value. Point clouds roughness is calculated as a distance  $\pm d$  from each point to a plane fitted on his neighbours within a radius  $r = d$ .

401 more than 1  $mm$  were filtered out. Additionally  
 402 sparse points were also removed before the registra-  
 403 tion in order to reduce the possible influence of  
 404 different point cloud densities in the registration<sup>6</sup>.  
 405 Table 2 shows the residuals and the statistics for the  
 406 scans co-registration. Scans from the interiors, all  
 407 placed along the longitudinal axis and featured by  
 408 high overlap, were co-registered incrementally using  
 409 the ICP implementation in CloudCompare<sup>7</sup>. Over-  
 410 lapping percentage among the scans from the exter-  
 411 iors was significantly lower, occurring only between  
 412 adjacent pairs. Consequently different registration

<sup>6</sup>The filter employed calculates the standard deviation of the mean distances from a point to his neighbours and rejects points with higher values.

<sup>7</sup><https://www.danielgm.net/cc/>

413 approaches were chosen for the exteriors: in 2016  
 414 markers were placed on the scene so co-registration  
 415 was target-based, while the 2018 scans were regis-  
 416 tered automatically using a global co-registration  
 approach implemented in Scene<sup>8</sup>.

Point cloud	RMSE ( $mm$ )	Overlap (%)	Scan points (M)
2016 int.	4.3	82%	59
2016 ext.	2.8	57%	24
2018 int.	3.0	91%	84
2018 ext.	2.3	59%	120

Table 2: Co-registration statistics. For each co-registration the mean values for the residuals, the pairs overlap and the total number of points are shown. The registration of the 2016 exteriors was target-based.

417

#### 418 4.5. Deformation analysis

419 To avoid any bias that could affect the results  
 420 of deformation analysis, a set of tie points placed  
 421 on the basement and the floor of the temple were  
 422 manually identified as stable areas for the exteriors  
 423 and interiors registration respectively. The main  
 424 purpose of this deformation analysis was indeed to  
 425 detect and quantify the permanent relative move-  
 426 ments of the structural elements due to the Chauk  
 427 earthquake, while the absolute movements of the  
 428 entire building were out of the scope of this re-  
 429 search. Tie points were measured on the 2018 point  
 430 clouds which have been registered on a set of GCPs,  
 431 independently measured with the total station from  
 432 the traverse benchmarks. Table 3 shows the resid-  
 433 uals for the 2018 survey registration with GCPs  
 434 and the registration of the 2016 point cloud on the  
 2018 one, using the selected tie points. Two tests

Point cloud	RMSE ( $mm$ )	Points
2018 int. - GCPs	2.5	5
2018 ext. - GCPs	4.6	6
2016 - 2018 ext.	3.2	5
2016 - 2018 int.	3.3	4

Table 3: Residuals on the GCPs used for the 2018 survey registration and tie points for the alignment with the pre-earthquake one.

435

436 were conducted using the C2M and M3C2 meth-  
 437 ods. They were chosen because both have been

<sup>8</sup><https://www.faro.com.>



438 proven to be less influenced by point cloud roughness and spatial density, both allowing the calculation of the signed distance, while the C2C methods usually gives only an absolute value as result. 441 The signed distance computation is quite relevant in structural monitoring as it can be used to qualify the kind of deformation occurred. 442 The surface reconstruction was performed using the Screened Poisson method, which is a very popular approach for surface reconstruction [27, 28]. 443 The algorithm requires the computation of normals, whose direction is consistent for all the point set. 444 Given the regular shape of the object normals estimation was performed separately with a new innovative approach and the same data used for the two comparisons [29]. 445 The chosen method uses the Hough Transform technique<sup>9</sup> to detect the edges [32] and a Convolutional Neural Network (CNN)<sup>10</sup> to learn the parameters of the function mapping the normals, basing on the point cloud features, like density, outliers and noise. 446 The method is very effective for application to sharp-edged surfaces and large point cloud data sets. 447 Three tests were performed to choose the meshing level of accuracy, using the spatial sampling of the octree structure. 448 Table 4 shows the statistics from the meshing process of the 2018 exteriors point cloud. 449 Starting from an octree cell with a 6 mm side at level 12, the noise from different scans point spacing was becoming visible, so level 11, with a 12 mm cell was chosen. 450 For all the tests the denser point clouds from the 2018 survey were chosen as reference, while the 2016 survey was the compared one, to avoid any possible error due to a different spatial sampling between the two sets. 451 Different spatial samplings within the survey scans and within the single scans were addressed during the co-registration step with a statistical filter (see subsection 4.4).

## 476 5. Results and Discussion

477 Table 5 summarizes the main parameters involved and obtained from the tests performed on

<sup>9</sup>The Hough Transform [30, 31], originally developed to detect simple features in 2D space, was later extended to detect any arbitrary feature in the 2D and 3D space and is widely used technique in several Computer Vision applications.

<sup>10</sup>CNNs are multilayered Artificial Neural Networks (ANNs) widely used to solve machine learning and data mining problems, ANNs are computing systems inspired by the functioning of neural networks in the animals brain.

Octree level	Side size (mm)	Triangles (M)
11	12	13
12	6	35
13	3	139

Table 4: Statistics of the 2018 exterior point cloud meshing. 86M of points were sampled to build the surface

479 the masonry walls. The results of sonic tests allowed to estimate that the average Young's modulus of the masonry walls of the temple is equal 0.46 GPa, in which the highest value is 1.1 GPa (recent masonry with cement based mortar) and the lowest value is 0.25 GPa (deteriorated original masonry). 480 The lowest value, corresponding to the most damaged part of the structure detected by the damage survey (Figure 8), has been discarded.

### Mechanical properties for the masonry

Samples	E [GPa]	V [m/s]	$\rho$ [Kg/m <sup>3</sup> ]	$\nu$ [-]
Direct tests	0.41	~280.0	1777	0.2
Indirect tests	0.50	~310.0	1777	0.2

Table 5: Summary of sonic testing results

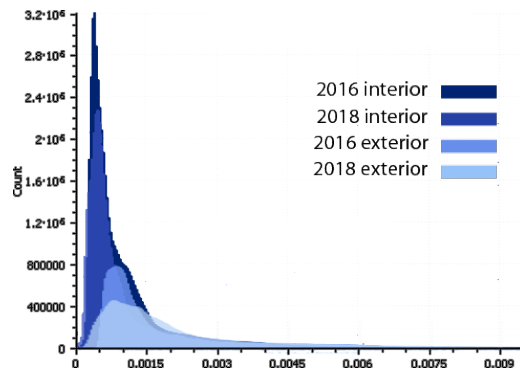


Figure 6: Standard deviations of the point clouds used for the comparison test with the M3C2 method (search radius  $r = 2\text{ cm}$ ). Values show the deviation of the points from the tangent plane computed locally from the normals.

Point clouds comparison with the M3C2 method test was performed with a maximum distance for correspondences search chosen to avoid false positive results due to the highly detailed wall surfaces

of the temple. Although the presence of holes in one of the two cloud is computed by the M3C2 algorithm as an undefined value, the presence of other points, belonging to other parallel portions of the surface, can result in a false correspondence if it is within the search distance limit. Thus the limit for the search distance was set to a value of 10 cm so that two parallel surfaces would not have been intersected along the normal direction. A different test was conducted to determine the best radius for the correspondence search within the tangent plane. Results of the test on the search radius are summarized in the figure 7 and indicate that for radii  $> 2\text{ cm}$  the maximum uncertainty is  $\sim 10\text{ mm}$  while for smaller values it increases to  $\sim 30\text{ mm}$ , so that almost all the deformations in that area are undetectable. Figure 6 shows the standard deviation distribution across the point clouds used for the test.

Figure 10 shows a map of the deformations oc-

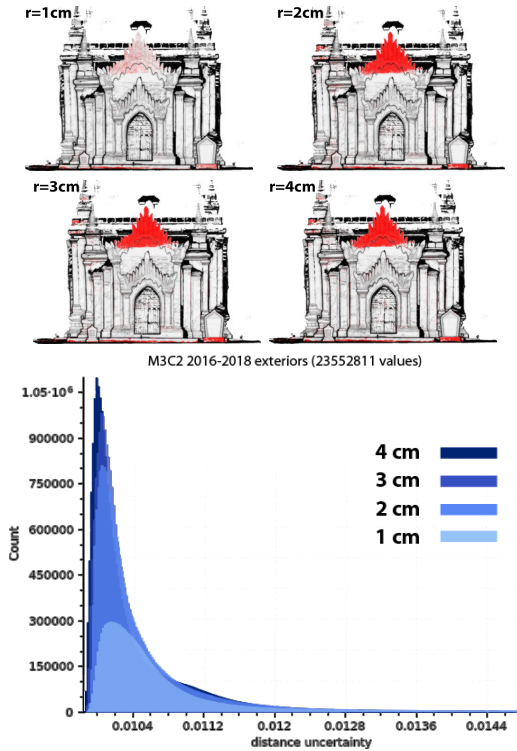


Figure 7: Distance uncertainties on the same M3C2 comparison tested with different search radius values and the effect on significant changes detection in the front façade (red points).

512 curred in the interiors measured with the M3C2  
513 method. Here the main deformations are in the  
514

515 main room, where small portions of the wall coat-  
516 ing, up to 4 cm thickness, detached after 2016.  
517 In figure 9 results of the exteriors comparison on  
518 the front façade performed with both the meth-  
519 ods (C2M and M3C2) are shown. In the exteriors  
520 the main significant changes occurred in the upper  
521 par of the tympanum which tilted forward after the  
522 2016 earthquake. At the top of the tympanum the  
523 measured displacement along the perpendicular di-  
524 rection was of thereabout 3 cm.

525 Although a comprehensive comparison of the dif-  
526 ferent algorithms for point clouds comparison was  
527 out of the scope of the present paper, the test con-  
528 ducted on the exteriors show significant differences  
529 between the results of the C2M and M3C2 analyses.  
530 As expected they both show a similar deformation  
531 on the upper part of the tympanum in the front  
532 façade, however preliminary results of the tests in-  
533 dicate the C2M method has potentially bigger un-  
534 certainties. Indeed table 6 shows the standard de-  
535 viation is about two times bigger with the C2M  
method.

C2C test	SD (mm)
C2M exteriors	24
M3C2 exteriors	10
M3C2 interiors	7

Table 6: Standard deviation of the values distribution from the exteriors, compared with the C2M and M3C2 methods.

## 6. Conclusions

537 This paper presents a study on advanced non-  
538 destructive techniques for the conservation of  
539 historic buildings. The Loka-Hteik-Pan temple  
540 (Bagan, Myanmar) was adopted and the applica-  
541 tion of the techniques was evaluated. The dam-  
542 age survey allowed to conclude that temple presents  
543 moderate damage, highlighted by the cracks in the  
544 South-East corner and the out-of-plane deformation  
545 of the tympanum of the North façade. The sonic  
546 tests allowed to identify the different types of ma-  
547 sonry of the structure and estimate their Young's  
548 moduli.

549 The deformation analysis with the TLS data has  
550 proven to be effective for detecting changes of 1 cm  
551 size or bigger. Moreover the M3C2 method used for  
552 distances computation is the more accurate avail-  
553 able at the moment because it takes into account  
554

555 all the error components, providing reliable results.  
556 Relatively small deformations and material losses  
557 can be efficiently detected and measured. Accuracy  
558 and efficiency can be improved with the use of a  
559 fixed set of GCPs placed outside the area where de-  
560 formations are to be searched, independently mea-  
561 sured and adjusted at each epoch. This GCPs net-  
562 work can be used exclusively for the registration of  
563 the surveys acquired in different times, while other  
564 sets of GCPs are used, if necessary, to register the  
565 scans acquired within the same period. This tech-  
566 nique is also more precise as avoid the propaga-  
567 tion of registration errors through the different sur-  
568 veys [13]. With this improvement portions of the  
569 building which are marked as being affected by de-  
570 formations can be checked efficiently and quickly  
571 with high precision without the need to survey the  
572 whole building at each time. Furthermore the de-  
573 tachments and deformations analysis can also be  
574 efficiently performed on site, allowing its results to-  
575 gether with those of the visual inspection to be used  
576 for guiding the sonic tests to be performed on the  
577 structure.

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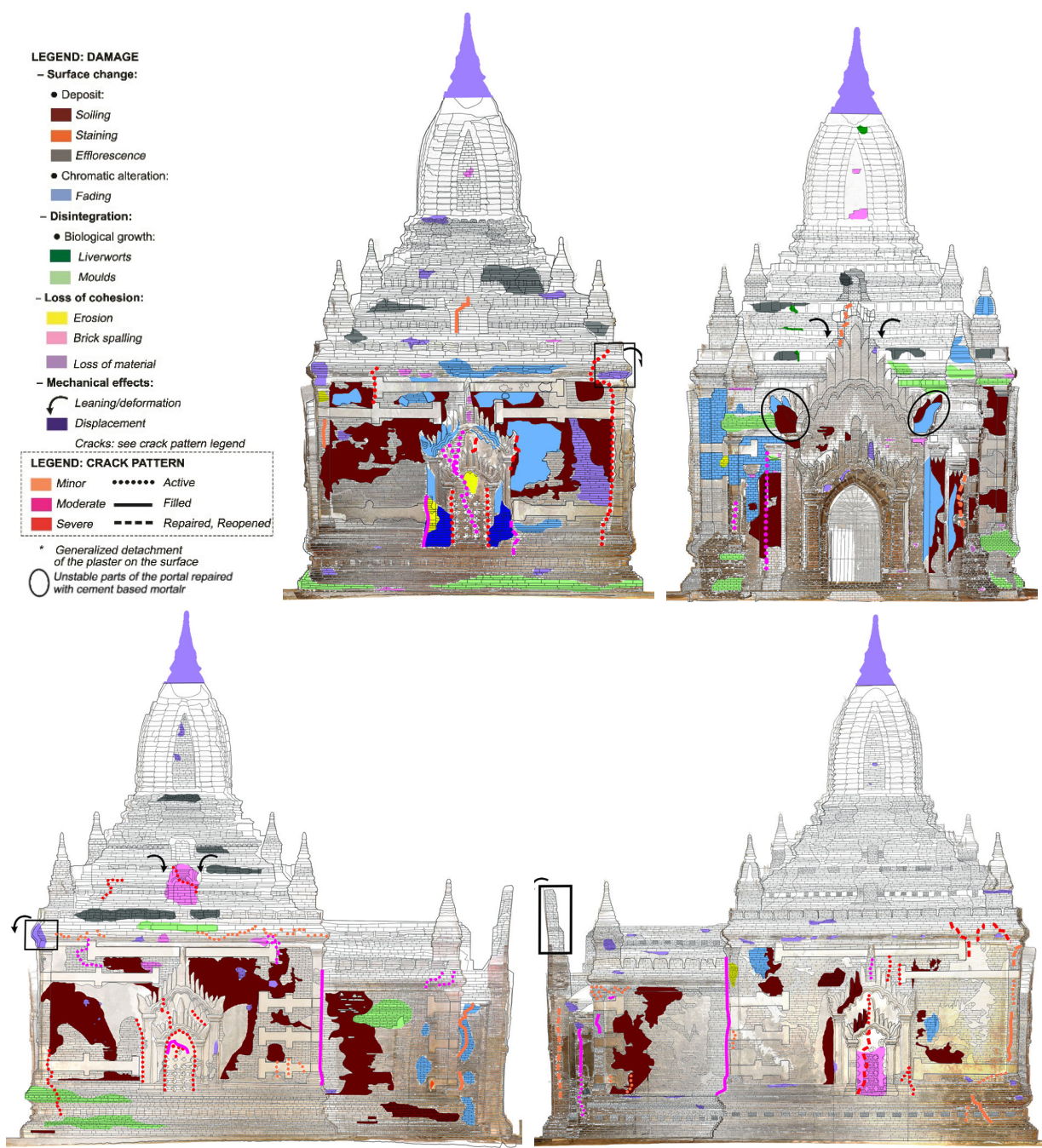


Figure 8: Deterioration mapping on the building elevations superimposed on the coloured point clouds from the 2018 survey.

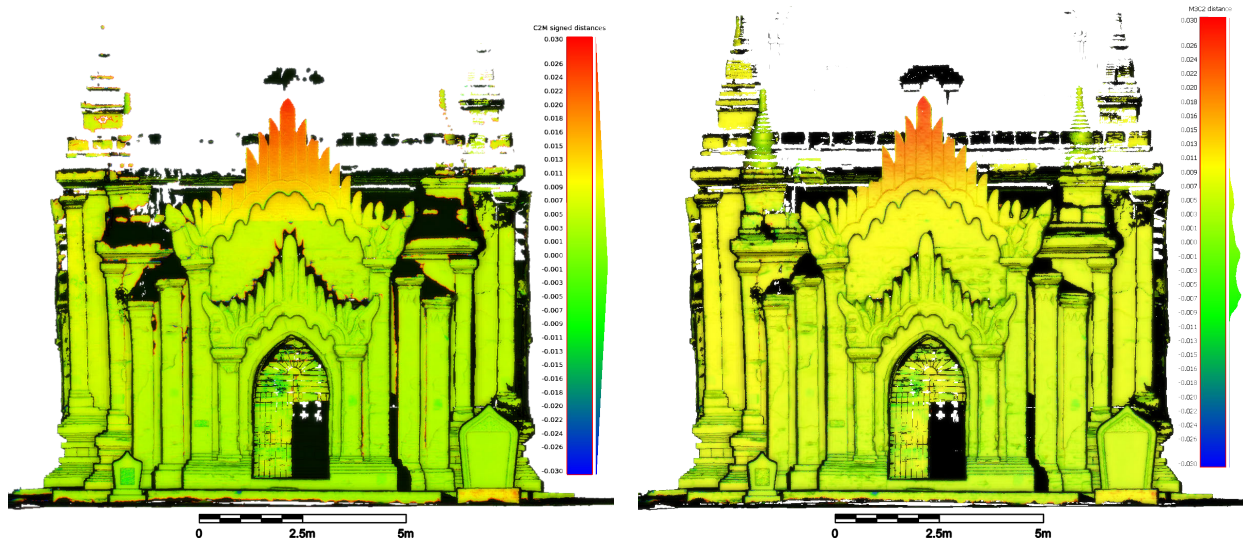


Figure 9: C2M (left) and M3C2 (right) exteriors comparisons, front view. Scale bar spans from  $-30$  to  $+30$  mm. On its right the distribution of the sample. Significant changes correspond to a forward movement of the upper part of the tympanum.

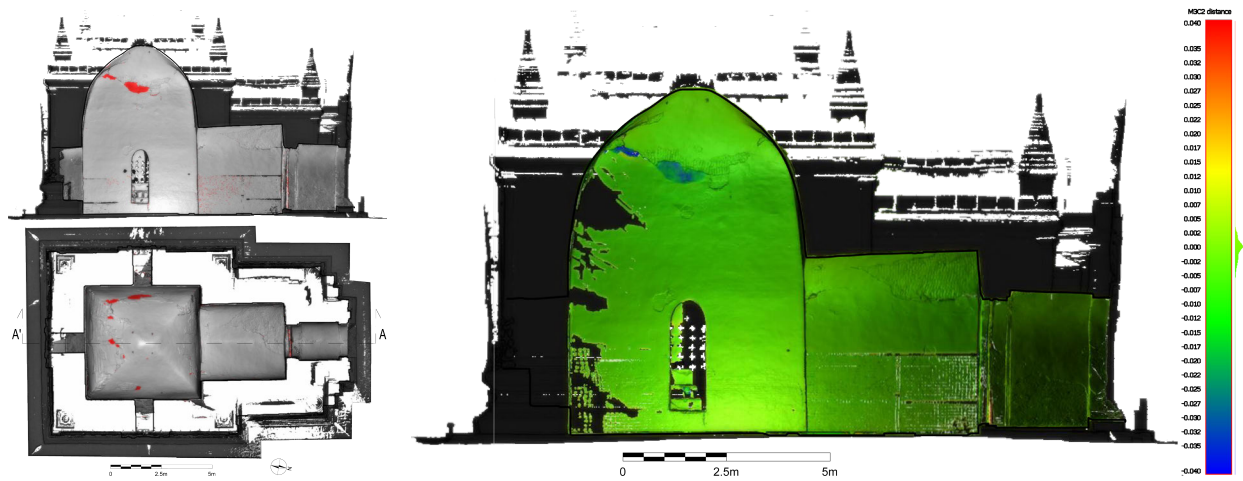


Figure 10: M3C2 interiors comparison, vertical section. Scale bar spans from  $-40$  to  $+40$  mm, on its right the distribution of the sample. Changes bigger than uncertainties are highlighted in red and correspond to plaster detachments in the main chamber vault. Outliers are visible in the lower portion of the antechamber (due to the barriers) and the door between the entrance and the antechamber.

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