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Advanced non-destructive techniques for the diagnosis of historic buildings: The Loka-Hteik-Pan temple in Bagan / Costamagna, Erik; Santana Quintero, Mario; Bianchini, Nicoletta; Mendes, Nuno; Lourenço, Paulo B.; Su, Su; Paik, Yin Min; Min, Aungzaw. - In: JOURNAL OF CULTURAL HERITAGE. - ISSN 1296-2074. - ELETTRONICO. - 43:(2020), pp. 108-117. [10.1016/j.culher.2019.09.006]

Availability: This version is available at: 11583/2807866 since: 2020-07-13T17:13:25Z

Publisher: Elsevier Masson SAS

Published DOI:10.1016/j.culher.2019.09.006

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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

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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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Preprint submitted to Journal of Cultural Heritage

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

2. Research aim 44

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The presented research was conducted in 2018 45 as a collaboration between Carleton University, 46 Mandalay Technological University and the De-47 partment of Archaeology and National Museums 48 of Myanmar. It involved a series of field activities, 49 workshops and conferences aimed to disseminate 50 the knowledge about Bagan archaeological site by 51 using innovative techniques for the documentation 52 and conservation of its cultural values. The site 53 includes thousands of religious buildings and was 54 affected by a series of seismic events over time, 55 104 the last of them in 2016. The object of study is 56 105 one of the temple which has been studied over 57 106 time and was damaged by the last earthquake 58 107 which destroyed the upper part of the roof. The 59 goal of this research is to show the effectiveness of 108 60 advanced non-destructive techniques that can be 61 110 deployed after an earthquake for a fast and reliable 62 111 assessment of seismic damages and guidance for 63 the interventions to be put in place. 64 113 65

3. Diagnostic techniques 66

3.1. Non-destructive testing 67

One of the older and simpler systems for 119 68 evaluating the structural heath of a building is 120 69 the direct visual inspection, which requires the 121 70 physical access to all the building parts and it 122 71 is strongly influenced by subjectivity [4]. On 123 72 the other hand, non-destructive techniques allow 124 73 to measure physical properties of the materials 125 74

which are crucial to determine the building seismic response. One of these techniques is sonic pulse velocity testing, which can be used to estimate the elastic properties of materials. This type of test is based on the propagation of waves inside the materials caused by an impulsive force. The velocity and the time spent to receive the signal, generated from the waves, can be read between the thickness of the internal and external surfaces of the walls (direct sonic tests) or along the same surface (indirect tests) at a specific distance. While visual inspection gives a general overview of the observed state of damage along the structure, the sonic tests are performed with the goal of evaluating the elastic properties through the reading of the velocity waves. Depicting the variation of velocity in different locations of the temple may correspond to an increase or decrease of the elastic properties due to internal cracks, deteriorations and/or detachments.

3.2. Point cloud processing Registration

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

Pre-determined associations between features from the two sets can be used for computing the parameters of the transformation. In this approach,

called target-based registration, markers are used 171 126 as tie points for the scans registration. In the 172 127 cloud to cloud approach no prior knowledge about 173 128 correspondences is given, these are automatically 174 129 found using points coordinates minimizing the 175 130 reciprocal distances between the clouds. Intensive 176 131 distance computations on point clouds are im- 177 132 proved using indexing structures like the octree [6], 178 133 which is an efficient hierarchical data structure 179 134 based on a regular space decomposition¹. A very 180 135 popular algorithm for the cloud to cloud fine 181 136 registration is the Iterative Closest Point (ICP) [7]. 182 137 This algorithm selects a set of samples from one 183 138 cloud and find point to point correspondences to 184 139 neighbours in the other set. The point to point 185 140 calculation method requires an high degree of 186 141 overlap between the pairs and an uniform point 187 142 density within the scans. 143 188 144 189

Spatial analysis and interpolation 145

Development of algorithms for the analysis of 146 spatial changes increased the effectiveness of us-147 ing LiDAR techniques and potentially extended 148 theirs application field for detecting and measuring 149 spatio-temporal changes without any prior knowl-150 edge. Deformation analysis and change detection 151 are the two main specialization of this topic, the for-152 mer dealing with the binary problem of distinguish 153 200 stable and unstable areas while the latter is focused $_{201}$ 154 on the accurate measurement of small changes, usu-155 ally close to the instrument tolerance. Change 156 detection techniques are usually applied to geo-157 sciences problems, where the co-registration of laser 158 scans acquired in different epochs on the base of 159 manually identified stable areas can be a challenge. 160 207 Automatic co-registration of laser scans and change 161 detection are indeed mutually dependent: registra-162 tion of scans affected by spatial changes requires 163 robustness against outliers (unstable areas), that is 164 the sampling of tie points only from stable areas. 165 212 This issue is addressed either using sequential [8] 166 and combinatory approaches [9]. Identification of 167 214 stable areas where to sample tie points for the laser 215 168 scans registration is usually less problematic when 169 216 the application field involves buildings, whose 3D 170

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

One of the first cloud comparison method developed was the cloud to model (or mesh) (C2M) [12] which can be used to compare point sets to surfaces models. Surface reconstruction from unstructured point clouds is performed by interpolating the points, usually with patches resulting in a facet model called mesh. While several approaches exist to find the best surface fitting for a point set, uncertainties introduced by interpolation are difficult to quantify. Methods for the cloud to cloud (C2C) comparison have also been developed, computing distances along normal directions without performing a surface reconstruction of the whole point set, but rather approximating locally the surface. Least squares planes, Delaunay triangulations and quadric surfaces are some of the models used as local best approximation of a point set, depending on the roughness and the level of detail [13]. Brodu and Lague proposed a C2C method called Model to Model Multiscale Cloud Comparison (M3C2) [14] which addresses some of the limitations of the other C2C approaches. First of all the algorithm computes normals for the whole point cloud to be compared at different scales, choosing the surface fitting which minimizes the difference in normal orientation between neighbour points. Thereafter the normals direction is used to project the neighbour points, whose mean value represents the average position of the points along that direction, while the standard deviation measures the roughness of the sampled points. Cloud to cloud local distance is thus computed as the distance between the two mean values. The SD is calculated for both the clouds and the results, together with the registration error (if available), are used to estimate the uncertainty of each measured distance, giving a local level of confidence for the C2C comparison. A statistical method for determining significant changes with the C2M method has also been proposed and used to test C2M against M3C2 [9]. M3C2 method has been tested in remote sensing [15] and closerange applications [16] with positive results. Detection and measurement of changes between two (or more) point sets acquired in different times requires the two sets to be registered using in the same Coordinate Reference System (CRS). The po-

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¹Given 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.

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

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4. Data acquisition and analysis 237

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

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

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

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

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

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 Central Myanmar during 20th and 21th centuries (See Figure 2), Loka-Hteik-Pan temple, as well as many other Bagan temples, underwent several structural and non-structural interventions. The most significant changes occurred after Bagan earthquake (1975), when locals funded heavy strengthening projects [23]. According to Pichard [19], "a reinforced concrete belt at the top of the walls" was inserted along the perimeter walls of the main chambers. 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 antechamber along the height of the structure. This work was supposed to be done in order to reestablish the connection between the walls.

Many portions of the portals and all the final parts of the pinnacles were rebuilt during the last century, using modern and industrial fired bricks. The Sikhara 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 Sikhara 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 replaced after this event and the highest part of the Sikhara, which did not collapse, was restored with the insertion of new bricks.

The frescoes were treated the first time in 1993, after 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 intervention on the mural paintings took place in 2015: liquid grout injection was employed to re-establish the adhesion of them on the walls.

4.2. Damage survey

The damage survey was evaluated through visual inspection in May 2018, aiming at updating the evaluation of the damage after the 2016 Chauk

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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].

Earthquake. Loka temple presents moderate dam-323 age at the connection between the two orthogonal 324 walls of the South-East corner, highlighted by two 325 vertical cracks from both the sides. In general, this 326 part suffers more damage than the other portions 327 of the monument and presents also a generalized 328 detachment of the corner along the entire height of 329 the temple. It is important to underline that this 330 damage located at South-East corner was already 331 noticed by Pichard [19] after Bagan Earthquake in 332 1975 and was yet present before the application of 333 reinforced concrete beams. In other parts of the 334 structure, there are many minor and medium cracks 335 along the boundaries between beams and masonry $_{_{343}}$ 336 surfaces. This kind of openings can be associated 344 337 to the incompatibility of the two materials in terms 345 338 of stiffness, strength and thermal effects. The tym- 346 339

panum of the North façade is visibly affected by
out-of-plane deformations and some parts of this 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.

tion of the bricks on the vaulted systems, both in the antechamber and the entrance, there is a longitudinal crack along the length of the vaults. As

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

the ortho-projection of the coloured point clouds 357

from the 2016 and 2018 surveys. 358

4.3. Sonic tests 359

Indirect sonic tests were carried out along all the external surface of the walls, at different heights, on surfaces composed both by original and modern bricks. Direct sonic tests were performed only close the North façade of the temple, because the 375 cross section of the walls in this location is visi-376 ble and accessible. The sonic tests were performed 377 in-situ during the technical visit in May 2018, us-378 ing an impulse hammer PCB, a piezoelectric ac-379 celerometer PCB $(\pm 0.5 g)$ and an acquisition board NI USB 4431. The tests were repeated more than 381 30 times per each location (17 locations of measure-382 ment along the structure) to give statistical stabil-383 ity 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-386 son's ratio ($\nu = 0.2$) and the velocity of the waves 387 $(VP = 280 - 310 \ m/s) \ [25].$ 388

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

4.4. LiDAR survey 360

Two different metric surveys of the temple 394 361 were performed using a Terrestrial Laser Scanner 395 362 (TLS)²³: in the 2016, before the Chauk earthquake 396 363 and in 2018, after the event. In 2018 a small tra-364 397 verse was established in the area of the temple. 365 Traversing was essential for aligning the exteriors 399 366

and interiors point cloud and for checking, with a different technique, the errors in laser scans registration. 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 $GCPs^4$. Table 1 shows the residuals on the benchmarks coordinates⁵.

The LiDAR surveys performed in 2016 and 2018

Station	X	Y	\mathbf{Z}
\mathbf{point}	(mm)	(mm)	(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.

covered all the exterior façades and the interiors of the temple. Figure 1 shows the position of the scans of the 2018 survey: a loop scheme was set for the exteriors while the scans from the interiors follow linear sequence, from the antechamber to the main room. A similar approach was used for the 2016 survey. Figure 4 shows the point spacing of the registered point clouds, computed with Meshlab [26] as the average distance from each point to his neighbours. Datasets from 2018 survey are a bit denser, especially regarding the exteriors, because the number of scan was doubled from 9 scans in 2016 to 18 scans in 2018, while for the interiors the number was almost the same (6 scans in 2016 and 7 in 2018). The sparser dataset (2016 exteriors) has 95% of the samples with a point spacing between 2 and 8 mm. Figure 5 shows that, apart from the small differences within the surveys, uncertainty deriving from point clouds roughness is below $8 \, mm$ for 95% of the sampled data in the worst scenario (2016 exteriors). These point cloud statistics show a potential tolerance of the metric information being extracted from the data in line with the goal to detect spatial changes of $1 \, cm$ size (or bigger). 9-Point clouds were re-sampled in order to reduce the point cloud density. Points closer one to each other

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 $^{^2\}mathrm{TLS}$ 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

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

⁴A Leica TS11 Total Station (TS) was used, with an angular accuracy of 3" and a distance accuracy of 1 mm + $1.5 \, ppm$ with standard prism and $2 \, mm + 2 \, ppm$ reflectorless

 $^{^{5}}$ Traverse adjustment were performed with the Least Squares (LS) method using the Microsurvey Starnet software.



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.

more than $1 \, mm$ were filtered out. Additionally 401 sparse points were also removed before the regis-402 tration in order to reduce the possible influence of 403 different point cloud densities in the registration 6 . 404 Table 2 shows the residuals and the statistics for the 405 scans co-registration. Scans from the interiors, all 406 placed along the longitudinal axis and featured by 407 high overlap, were co-registered incrementally using 408 the ICP implementation in CloudCompare⁷. Over-409 lapping percentage among the scans from the exte-410 riors was significantly lower, occurring only between 411 adjacent pairs. Consequently different registration 412

⁷https://www.danielgm.net/cc/

approaches were chosen for the exteriors: in 2016 markers were placed on the scene so co-registration was target-based, while the 2018 scans were registered automatically using a global co-registration approach implemented in Scene⁸.

Point cloud	$\begin{array}{c} \mathbf{RMSE} \\ (mm) \end{array}$	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.

4.5. Deformation analysis

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To avoid any bias that could affect the results of deformation analysis, a set of the points placed on the basement and the floor of the temple were manually identified as stable areas for the exteriors and interiors registration respectively. The main purpose of this deformation analysis was indeed to detect and quantify the permanent relative movements of the structural elements due to the Chauk earthquake, while the absolute movements of the entire building were out of the scope of this research. Tie points were measured on the 2018 point clouds which have been registered on a set of GCPs, independently measured with the total station from the traverse benchmarks. Table 3 shows the residuals for the 2018 survey registration with GCPs and the registration of the 2016 point cloud on the 2018 one, using the selected tie points. Two tests

Point cloud	\mathbf{RMSE}	Points
	(mm)	
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 preearthquake one.

were conducted using the C2M and M3C2 methods. They were chosen because both have been

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 $^{^6{\}rm The}$ filter employed calculates the standard deviation of 437 the mean distances from a point to his neighbours and rejects points with higher values.

⁸https://www.faro.com.

proven to be less influenced by point cloud rough-438 ness and spatial density, both allowing the calcu-439 lation of the signed distance, while the C2C meth-440 ods usually gives only an absolute value as result. 441 The signed distance computation is quite relevant 442 in structural monitoring as it can be used to qual-443 ify the kind of deformation occurred. The surface 444 reconstruction was performed using the Screened 445 Poisson method, which is a very popular approach 446 for surface reconstruction [27, 28]. The algorithm 479 447 requires the computation of normals, whose direc- 480 448 tion is consistent for all the point set. Given the 481 449 regular shape of the object normals estimation was 482 450 performed separately with a new innovative ap- 483 451 proach and the same data used for the two com-484 452 parisons [29]. The chosen method uses the Hough 485 453 Transform technique⁹ to detect the edges [32] and 486 454 a Convolutional Neural Network (CNN)¹⁰ to learn 487 455 the parameters of the function mapping the nor-456 mals, basing on the point cloud features, like den-457 sity, outliers and noise. The method is very effective 458 for application to sharp-edged surfaces and large 459 point cloud data sets. Three tests were performed 460 to choose the meshing level of accuracy, using the 461 spatial sampling of the octree structure. Table 4 462 shows the statistics from the meshing process of the 463 2018 exteriors point cloud. Starting from an octree 464 cell with a $6 \, mm$ side at level 12, the noise from dif-465 ferent scans point spacing was becoming visible, so 466 level 11, with a $12 \, mm$ cell was chosen. For all the 488 467 tests the denser point clouds from the 2018 survey 468 were chosen as reference, while the 2016 survey was 469 the compared one, to avoid any possible error due 470 to a different spatial sampling between the two sets. 471 Different spatial samplings within the survey scans 472 and within the single scans were addressed during 473 the co-registration step with a statistical filter(see 474 475 subsection 4.4).

476 5. Results and Discussion

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

Octree	Side size	Triangles
level	(mm)	(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

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). 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	\mathbf{E}	V	ρ	ν
	[GPa]	[m/s]	$[Kg/m^3]$	[-]
Direct	0.41	~ 280.0	1777	0.2
tests 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 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

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⁹The 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.

¹⁰CNNs 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.

of the temple. Although the presence of holes in 515 493 one of the two cloud is computed by the M3C2 al- 516 494 gorithm as an undefined value, the presence of other 517 495 points, belonging to other parallel portions of the 518 496 surface, can result in a false correspondence if it 519 497 is within the search distance limit. Thus the limit 520 498 for the search distance was set to a value of $10\,cm$ 521 499 so that two parallel surfaces would not have been 522 500 intersected along the normal direction. A differ- 523 501 ent test was conducted to determine the best ra- 524 502 dius for the correspondence search within the tan- 525 503 gent plane. Results of the test on the search radius 526 504 are summarized in the figure 7 and indicate that for 527 505 radii > 2 cm the maximum uncertainty is $\sim 10 \, mm$ 528 506 while for smaller values it increases to $\sim 30mm$, so 529 507 that almost all the deformations in that area are 530 508 undetectable. Figure 6 shows the standard devia- 531 509 tion distribution across the point clouds used for 532 510 the test. 511 533

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).

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 $_{513}$ curred in the interiors measured with the M3C2 $_{553}$ $_{514}$ method. Here the main deformations are in the $_{554}$ main room, where small portions of the wall coating, up to $4 \, cm$ thickness, detached after 2016. In figure 9 results of the exteriors comparison on the front façade performed with both the methods (C2M and M3C2) are shown. In the exteriors the main significant changes occurred in the upper par of the tympanum which tilted forward after the 2016 earthquake. At the top of the tympanum the measured displacement along the perpendicular direction was of thereabout $3 \, cm$.

Although a comprehensive comparison of the different algorithms for point clouds comparison was out of the scope of the present paper, the test conducted on the exteriors show significant differences between the results of the C2M and M3C2 analyses. As expected they both show a similar deformation on the upper part of the tympanum in the front façade, however preliminary results of the tests indicate the C2M method has potentially bigger uncertainties. Indeed table 6 shows the standard deviation 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.

537 6. Conclusions

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This paper presents a study on advanced nondestructive techniques for the conservation of historic buildings. The Loka-Hteik-Pan temple (Bagan, Myanmar) was adopted and the application of the techniques was evaluated. The damage survey allowed to conclude that temple presents moderate damage, highlighted by the cracks in the South-East corner and the out-of-plane deformation of the tympanum of the North façade. The sonic tests allowed to identify the different types of masonry of the structure and estimate theirs Young's moduli.

The deformation analysis with the TLS data has proven to be effective for detecting changes of 1 cmsize or bigger. Moreover the M3C2 method used for distances computation is the more accurate available at the moment because it takes into account

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

578 7. Acknowledgements

The authors wish to acknowledge Dr. U Kyaw 579 Oo Lwin Director General of the Department 580 of Archaeology and National Museum, Dr. Sint 581 Soe, Rector of Mandalay Technological University 582 and Mrs. Ohmar Myo of UNESCO Myanmar 583 for this unique opportunity to collaborate in the 584 conservation of built heritage in Bagan, Myanmar. 585 Other thanks go to all the students that par-586 ticipated in the documentation workshop from 587 Mandalay Technological University, Department of 588 Archaeology and Carleton University. 589

Furthermore, the authors would like to acknowledge the outstanding support staff of Carleton
Immersive Media Studio (CIMS). Finally, we
would like to thank all the individuals and institutions that helped with the completion of this article.



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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