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LASER SCANNING, MODELING, AND ANALYSIS FOR DAMAGE ASSESSMENT AND RESTORATION OF HISTORICAL STRUCTURES

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Abstract. *High-definition laser scanning is rapidly becoming an essential tool for accurate non-destructive three-dimensional measurements of structures. This technology provides valuable information about an object which is discretized in space as "point clouds". Two representative examples of current research activities on use of laser scanning in historic buildings in Uzbekistan and California are discussed. The first example is the Registan Square ensemble in Samarkand, Uzbekistan. The ensemble includes several heritage structures. Earthquakes, extreme seasonal temperatures, etc. have left the ensemble in a ruined condition. Domes and portals were partially or totally destroyed. The minarets were dangerously inclined, and some façades lost 70-80% of their ceramic tile coverings. Structural repairs and straightening of the minarets had been conducted over the years. In this study, the ensemble was scanned from about 70 positions to capture the current condition of the historic structures and to conduct structural assessment of the ensemble and its components. The scan data are expected to be used for monitoring of the ensemble's structural condition. In addition to visual scan data inspection, detailed finite element model of the ensemble was generated from the as-found geometry captured by laser scans. This model allows detailed seismic analysis of the monuments and its components. The model developed for the Sher-Dor Madrasah, part of the ensemble, using the scan data and sample preliminary analysis results are presented in this paper. The research team also investigated several historic buildings damaged during the 2014 South Napa Earthquake, California, USA, as the second example. In that regard, structural damage assessment using laser scanning for several historic buildings, including three churches, were conducted. The results of one of the damaged churches are discussed herein.*

1 INTRODUCTION

Laser scanning technology is rapidly expanding into many fields and becoming an essential tool for accurate non-destructive three-dimensional (3D) measurements of structures. This technology enables users to capture many points from the subject structure with high accuracy. In particular, high-definition laser scanning (HDS) technology provides both qualitative and quantitative information about a complex object which is discretized as a cloud of millions or billions of points in space. Nowadays, the HDS technology is going beyond the limits of its traditional usage, namely topographical surveying, reverse engineering, etc., and is finding excellent applications in several fields, e.g. scanning surfaces of visible faults in earthquake-prone regions and analysis of their roughness led to new developments in seismology [1]. Extensive studies of heritage buildings are being conducted for historic places throughout the world, e.g. [2]. The HDS has been extensively used for documentation and damage assessment of test structures subjected to earthquake loads at the University of California, Berkeley (UCB) [3]. In that regard, a unique study of the accuracy of laser scans compared to conventional measurements on a shaking table test of a seismically vulnerable two-story wood house over garage due to soft story and torsional effects was conducted [4].

This paper extends the ideas presented earlier [3-5] and uses laser scans as a tool to capture as-found geometry of historic structures. The geometry is used in generation of accurate finite element (FE) models to be used for detailed structural assessment, seismic analysis, and development of retrofit strategies.

2 LASER SCANNING OF HISTORIC BUILDINGS IN UZBEKISTAN

An extensive program of laser scanning of historic monuments in Uzbekistan was conducted in October 2013. As a representative example of many heritage monuments, the Registan Square ensemble in Samarkand, Uzbekistan was selected. The ensemble includes the Ulugh Beg Madrasah, 1417-1420, the Sher-Dor Madrasah, 1619-1636, the Tilya-Kori Madrasah and Mosque, 1646-1660, and the 18th century Chorsu domed market as shown in the Google map presented in Fig. 1. Earthquakes, extreme seasonal temperatures, normal depreciation of the buildings and the economic crises of the 18th and 19th centuries had left the ensemble in a ruined condition. Domes and portals were partially or, in some cases, totally destroyed. The minarets were dangerously inclined, and façades in some places had lost 70-80% of their ceramic tile coverings. Structural repairs and straightening of the minarets had been conducted in 1923 and 1932. However, the major restoration works were undertaken in recent years. The ensemble is in its best condition since late 19th century, although some inclination and cracks can be observed in the portals, minarets, and the domes of the monuments. In the course of this study, the ensemble was scanned from about seventy positions (scan stations). The main objective of this scanning program was to capture the current conditions of the historic monuments and conduct structural assessment of the ensemble and its components. A detailed FE model of the ensemble was generated from the as-found geometry captured by laser scans. The model was utilized for detailed seismic analysis of the monuments and its components. The scan data produced extremely valuable results that could be used in determining further restoration strategies of the monument located in this earthquake-prone area of Central Asia. The scan data are expected to be regularly used for monitoring of the ensemble's structural condition. This paper presents some representative examples of this extensive program.

Fig. 1. Google map of the Registan Square ensemble

3 VISUAL ASSESSMENT OF CURRENT CONDITION

The Registan Square ensemble has a long and rich history of being one of the major centers of ancient culture. It is one of the major historic ensembles of Samarkand. The city is most noted for its central position on the Great Silk Road, the trade route between China and the West, and for being an Islamic center for scholarly study. In the 14th century, Samarkand became the capital of the Timurid Empire. The Registan was the center of the ancient city. The economic crises of the 18th and 19th centuries had left the ensemble in a ruined condition. Typical images of the Ulugh Beg Madrasah, the Tilya-Kori Madrasah, and the Sher-Dor Madrasah dated to the late 19th century are presented in Figs. 2(a), 3(a), and 4(a), respectively. These photographs are taken by G. A. Pankratiev [6], a Russian army captain and amateur photographer. He produced a unique series of photographs of the architectural monuments and images of the city of Samarkand between 1894 and 1904. As shown in the images, the domes and portals of the monuments remained in extremely poor shape from a structural and an esthetics' point of view. Moreover, the minarets and portals were dangerously inclined. A large number of the ceramic tile coverings were lost from the façades due to deterioration. Structural repairs and straightening of the minarets had been conducted in 1923 and 1932. Several other restoration efforts have taken place in recent years.

As a result of all restoration efforts (shown in Figs. 2(b), 3(b), and 4(b)), the current condition of the ensemble is significantly better than it used to be in the late 19th century. Nevertheless, there are evidences of structural anomalies in the ensemble's monuments. For example, a visual observation reveals the following: 1) A large crack in the dome of Tilya-Kori Mosque, 2) An inclined minaret on North-West side of the Ulugh Beg Madrasah, and 3) A visible misalignment in the Ulugh Beg Madrasah's portal. The current view of the whole ensemble is presented in Fig. 5. The Ulugh Beg Madrasah is on the left side, the Tilya-Kori Madrasah and Mosque are in the center, and the Sher-Dor Madrasah is on right side of the image.


(a) View in 1890 (after [6]) (b) Current view

Fig. 2. Main entrance of the Ulugh Beg Madrasah


(a) View in 1890 (after [6]) (b) Current view

Fig. 3. Main entrance of the Tilya-Kori Madrasah and Mosque (Note that the mosque dome is not present in the old photo (a))


(a) View in 1890 (after [6]) (b) Current view

Fig. 4. Main entrance of the Sher-Dor Madrasah

Fig. 5. Current view of the Registan Square ensemble.

4 CURRENT CONDITION BY LASER SCANS AND FE MODELING

All three monuments were scanned by means of P20, a high-definition laser scanner manufactured by Leica Geosystems, Inc. The scans were conducted from about seventy positions (stations). The individual scans were stitched (registered) together in Cyclone application [7]. As a result, a fully stitched point cloud (registration) contains the geometric details of all three monuments. A typical result is presented in Fig. 6 that shows registration of the Tilya-Kori Madrasah and Mosque. The scans were conducted from all positions, including: inside of the monument, in the courtyard, around the exterior wall, and on the roof. Therefore, the registration documented the spatial locations of all surfaces.

In addition to the global dimensions of all monuments located within the ensemble, the scans captured all details of the monuments, namely tile shape, dimensions, and their locations in the monuments, any imperfections, and the overall geometric shapes of the portals and facades. To achieve this level of detail in point density, all scans were conducted with a density of 2 mm by 2 mm. One of the typical results for a portal is shown in Fig. 7. In addition to spatial locations of the details, the colors from the built-in camera and intensity colors of the reflected light (closely correlated to an object's color) were also documented.

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One of the main objectives of the project was the development of finite element models based on the as-found geometry of the monuments and subsequent detailed structural analysis of their vulnerability to the seismic effects. Examples of how this objective was achieved are presented in this section of the paper.

The Cyclone application [7] is capable of reducing a point cloud into a mesh. This option was utilized for surfaces with complex geometry, approximation of which by a regular mesh is not practical. A typical example of a ceiling in one of the two main entrances into the Sher-Dor Madrasah is presented here. A small portion of the point cloud extracted from the full registration is presented in Fig. 8.

The point cloud of the ceiling surface reveals its irregular and complex geometry as shown in the top view of the point cloud in Fig. 9a. This complex surface is approximated in Cyclone [7] by a mesh as presented in Fig. 9b. The vaults supporting the ceiling are removed from the mesh to simplify the presentation.

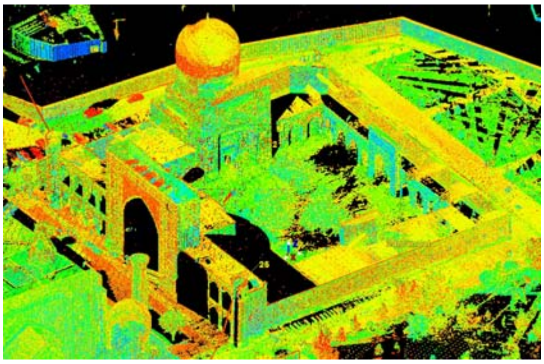


Fig. 6. Registration of the Tilya-Kori Madrasah and Mosque.

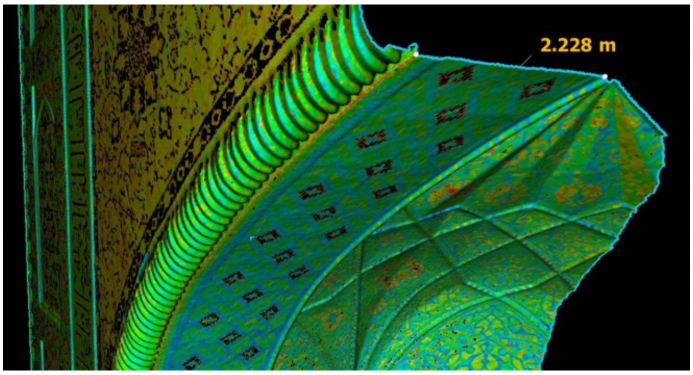
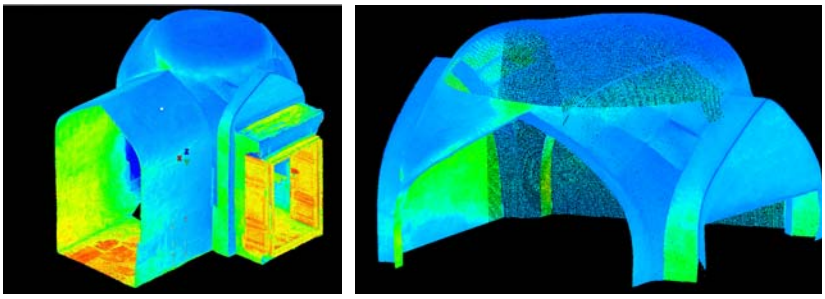
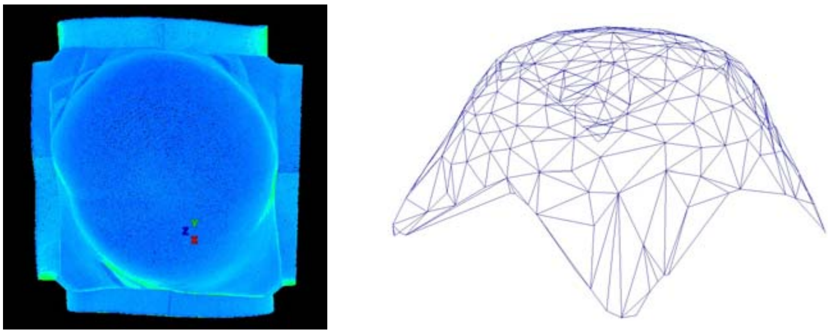


Fig. 7. Tile details captured by laser scans.



(a) Part of full registration (b) Global view of the ceiling

Fig. 8. Point cloud of north side entrance to the Sher-Dor Madrasah.



(a) Top view of the ceiling (b) Mesh capturing irregular ceiling surface

Fig. 9. Irregular surface of the ceiling in the Sher-Dor Madrasah's entrance.

To simplify the presentation of the point cloud, the main part of the Tilya-Kori Mosque was extracted from the full registration. Horizontal slices of the point cloud were introduced at several elevations. The slices contain a massive amount of information about the global geometry, dimensions, and structural anomalies. Some representative results are discussed here. The first horizontal slice was introduced at the highest point of the floor. Fig. 10 presents a horizontal slice at 0.20 m above the floor. Detailed analysis of the plan view revealed that there is an opening between the tiles on the West side of the mosque. This opening is about 11 cm deep as shown in this figure.

The identified opening, discussed above and shown in Fig. 10, can be related to a crack in wall that was observed earlier [8]. During this review, it was observed that there was a crack in one of the vaults in the Tilya-Kori Mosque. It was concluded that this can be the result of a low load bearing capacity of the underlying soil that can compromise the structural integrity of the monument in the long run or during an earthquake. It is to be noted that the vaults represent the major load-bearing structural elements in all monuments of the ensemble.

The horizontal slice provided an estimate of an overall thickness of the west side wall as shown in Fig. 11. This estimate includes the thickness values of the tiles on both sides of the wall, the mortar attaching the tiles to brick walls, and the brick wall itself.

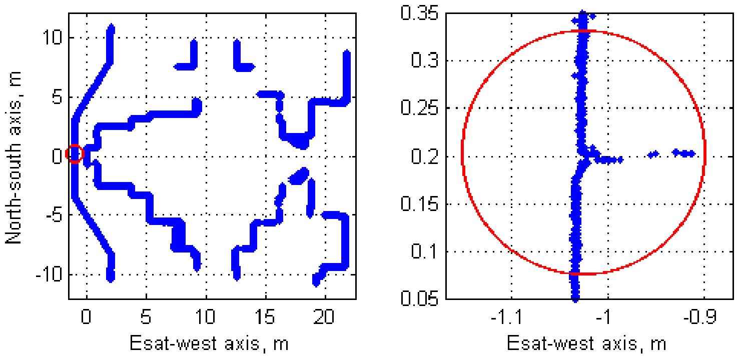


Fig. 10. Opening in west side wall of Tilya-Kori Mosque (about 11 cm deep)

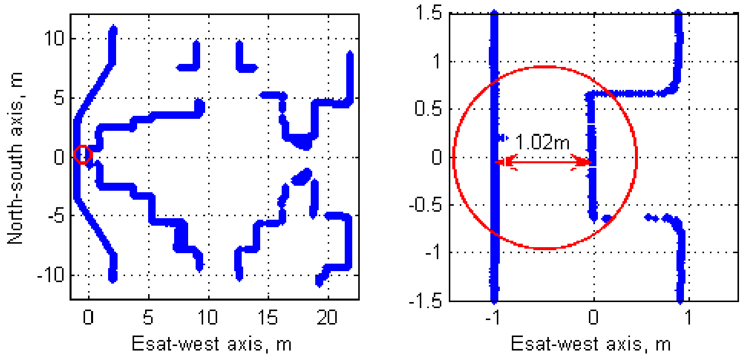
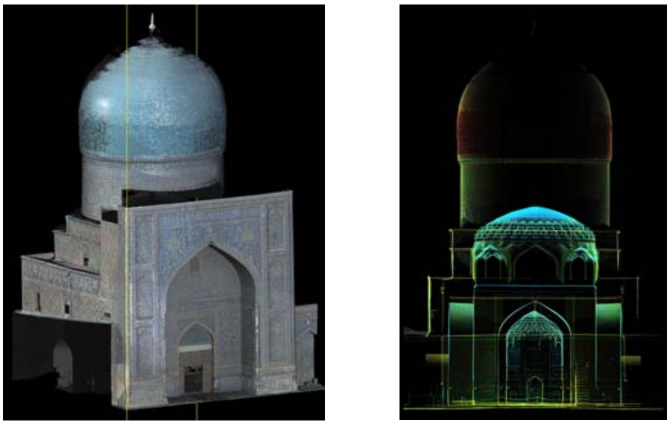


Fig. 11. Thickness of west wall of Tilya-Kori Mosque with tiles on both sides

The left images of Figs. 12 and 13 show the isometric view of the Tilya-Kori Mosque in colors obtained from the scanners' still imaging camera and point cloud. The right image of Fig. 13 presents the half-space view of the west half of the mosque. The details required for structural modeling and analysis (wall thickness and its dimensions for example) are obtained from the half-space and thin slices as presented in Fig. 13.

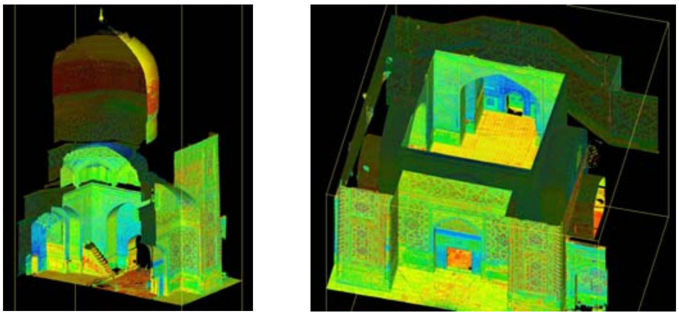
Since the majority of the scan stations were conducted from ground level, the dome of the Tilya-Kori Mosque was not captured completely. This shortcoming was anticipated and is attributed to the limited duration of the field work. This problem was addressed by making sure that the scan positions are providing a view of the observed crack in the dome from as many positions as possible. To cover this surface with maximum efficiency, two stations from the roof and more than 20 stations from the ground level of the courtyard and outside of the exterior wall area were utilized. This approach was successful in capturing the majority of the dome surface. The resulting stitched point cloud of the Tilya-Kori Mosque extracted from the full registration of the whole ensemble is shown in Fig. 14.

Modeling of the dome, shown in Fig. 14, was one of the main objectives of the study since there was a visible crack on the east side of the dome. The mesh generation option provided by Cyclone [7] was not utilized in this case because a mesh with a regular size was preferred for this monument. The regularly spaced meshing was based on utilization of 5 mm thick horizontal slices as shown in Fig. 15 showing two vertical cross sections perpendicular to each other and located at the North-South and East-West planes. They are plotted on top of each other to demonstrate the differences in the geometry of the dome, refer to the bottom left portion of the image where arrows point at the region with inconsistent geometry.



Isometric view in camera colors — Elevation showing west half

Fig. 12. Point cloud of the Tilya-Kori Mosque.



Isometric view — Half-space view showing west half

Fig. 13. Slice views of the Tilya-Kori Mosque.

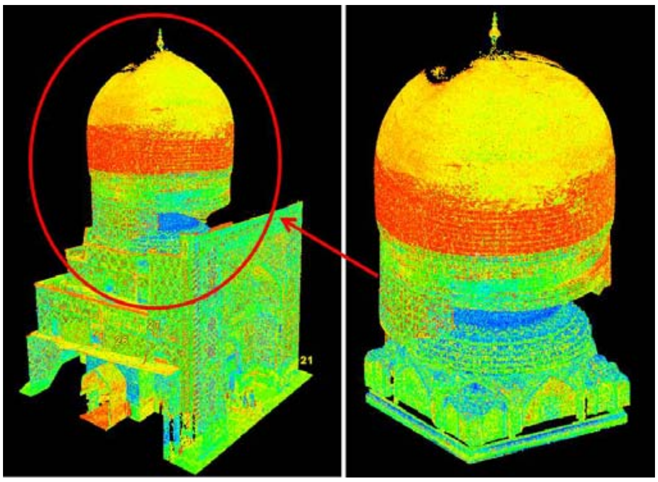


Fig. 14. Point cloud of dome.

At all other locations, the sections perfectly match each other, which demonstrates the accuracy of the dome's design and construction. It is worthy to note that the dome was constructed after 1976 [9] and as such represents a large and heavy addition to the monument that can challenge the load-bearing capacity of the vaults.

The mesh of the dome was generated at the elevations identified by the green dashed lines in Fig. 15. To have strong control over the meshing procedure while maximizing usage of the point cloud, a special set of programs was prepared in Matlab [10]. The mesh was generated by using the points of the cloud that were present in the vicinity of a regularly spaced mesh. In the shadow zones, where points were missing in the point cloud, the following procedure was used. The horizontal slice of a point cloud was approximated by a circle using a best fit procedure applied to the scanned points of the surface. The mesh in the shadow zones were selected based on these circles. A resulting mesh is presented in Fig. 16.

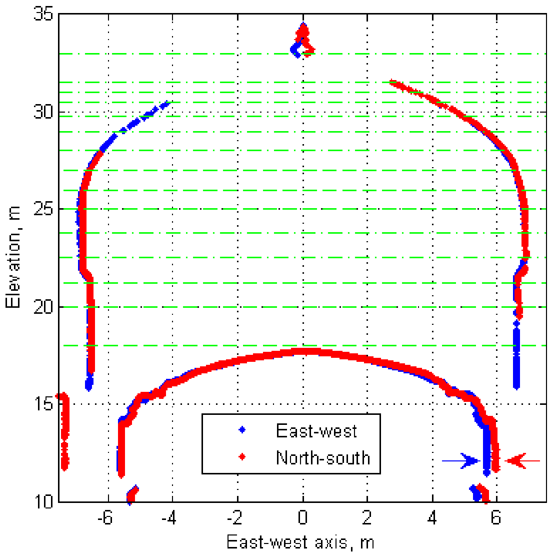
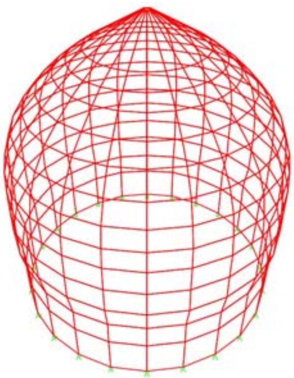


Fig. 15. Vertical slices of the Tilya-Kori Mosque where elevations of horizontal slices are shown by dashed green lines.

(a) Current photograph



(b) Regularly spaced mesh

Fig. 16. Regularly spaced mesh of the Tilya-Kori Mosque's dome.

A visual observation of the minarets of Ulugh Beg Madrasah revealed that one of the minarets, namely the one on the North-West side of the monument, is inclined. The visual observation failed to estimate the overall direction of the inclination and its dependency on the minaret's elevation. The point cloud of the minaret provided answers to these questions based on detailed information on the surface points captured by a laser scanner. A small portion of the full registration of the monument was analyzed for this purpose which consisted of the point cloud of the minaret and two outside walls. The total number of points was close to 20 million. This allowed us to capture the surface with much more detail. Several horizontal slices of this portion of the point cloud revealed the following results. First, the angle between the walls is very close to 90 degrees, as presented in Fig. 17 by red arrows.

Second, the minaret is mainly inclined away from both walls. Therefore, the overall direction of inclination from the walls is close to 45 degrees, as shown in Fig. 18 (horizontal direction in the plot). The inclination of the minaret was noticed earlier [9] and it is mostly related to the uneven settlement of the underlying soil.

Third, a large portion of the tiles are bulging out at the bottom of the minaret in the direction of the inclination as shown in Fig. 19. The bulging portion of the tile covering represents large compression forces in this part of the minaret. As a result, the tile covering is buckling away from the minaret's wall at this location. This is most likely associated with the fact that the center of gravity of the minaret is shifted towards the bulging region. Therefore, the mass distribution in the cross-section is mainly concentrated next to this region. The dense point cloud displaying many details of the minaret's tile covering is presented in Fig. 20a. A zoomed view of the bulged region where the tile cover has buckled away from the wall is presented in Fig. 20b.

The mesh of the minaret was generated by utilizing the approach described above and it was based on a best fit of the sections of the point cloud using circles. The resulting regular mesh has fine spacing at the elevations where the bulging has occurred and coarse spacing elsewhere. The mesh was generated for two conditions of the minaret, namely the current inclined condition and the so-called "original", where the axis of the conic surface of the minaret is vertical. The latter assumes that the minaret was plumbed during its original construction. The meshes were generated at the elevations shown with dashed green lines in Fig. 19. The meshes generated from the point cloud and representing the current inclined and the 'original' conditions are shown in Fig. 21.

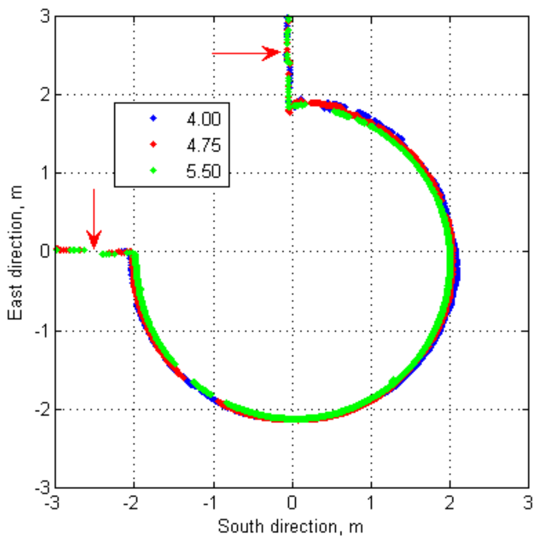


Fig. 17. Horizontal slices at bottom of one of the minarets of the Ulugh Beg Madrasah.

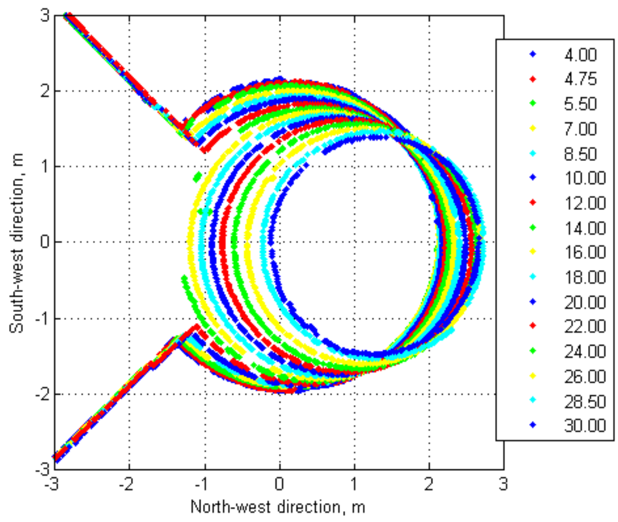


Fig. 18. Horizontal slices along the elevation of one of the minarets of the Ulugh Beg Madrasah.

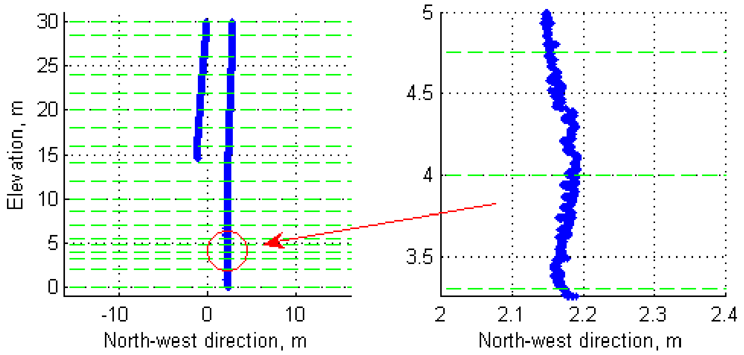


Fig. 19. Vertical slice of one of the minarets of the Ulugh Beg Madrasah at 45 degrees to the walls (bulged section is shown on right).

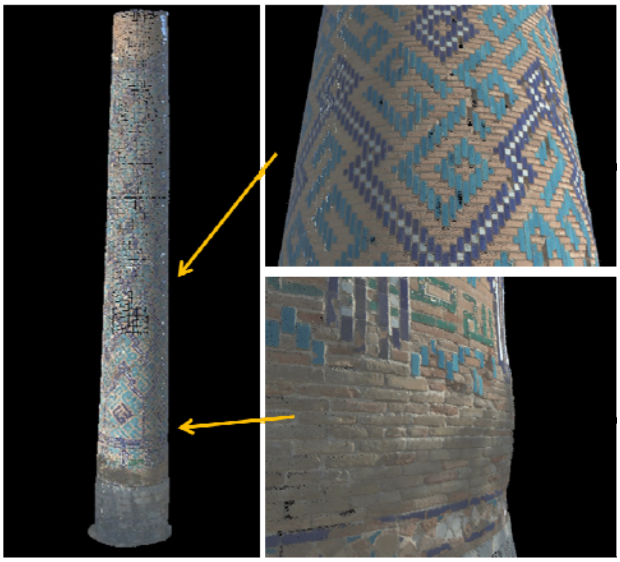
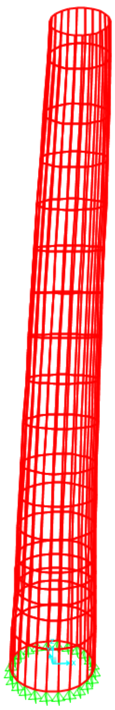


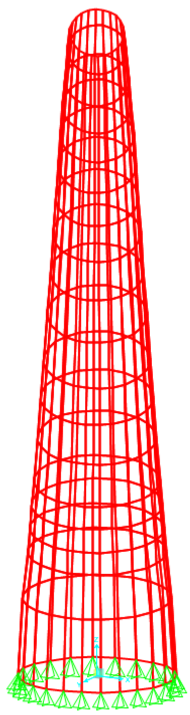
Fig. 20. Point cloud displaying the details and the bulged region of one of the minarets of the Ulugh Beg Madrasah.

From a geometric point of view, the minaret represents a tapered cone without a tip. Therefore, it is not simple to estimate its inclination since the surface of the cone is tapered. To estimate the inclination of the minaret, the special procedure was devised as discussed in this paragraph. Analysis of shapes of the horizontal slices from the point cloud of the minaret revealed that all sections can be closely fitted by circles. The radii of these circles were used for the estimates of the original taper and the circle's origin locations were used to estimate the global direction of inclination. The results of this procedure are presented in Fig. 22 where the green straight lines represent linear best fits of the radii of the circular cross-sections and the corresponding inclinations. Based on these linear approximations, an estimate of 4.6% inclination was obtained. It is to be noted that the original taper of the minaret is estimated as 2.3%.

It is worth noting that the inclination of the minaret's axis is very close to being linear. This observation can serve as evidence for the following two important remarks: (1) The structural connection between the walls and the minaret is most likely compromised and (2) The residual deformation (inclination) is most likely related to soft soil conditions (concentrated rotation at the base leading to the observed almost rigid body rotation of the minaret from the point cloud of the laser scanning) under the minaret. It is also noted that the adjacent walls of the monument end at about 12 meters of elevation and they have negligible effect on the inclination shape of the minaret, refer to Fig. 17. Hence, as a starting point for the planned detailed seismic analysis, the minaret can be analyzed independently from the walls and the rest of the monument. Subsequently, the next step is to take into account the evident soil-structure-interaction in the seismic analysis of the structure. It is to be stressed that the consideration of the soil-structure-interaction can be significant for this monument where its structural integrity is compromised by a soft underlying soil.



(a) Mesh generated from point cloud for current - inclined condition



(b) Mesh generated from point cloud for "original" condition

Fig. 21. Generated mesh of the inclined minaret of the Ulugh Beg Madrasah.

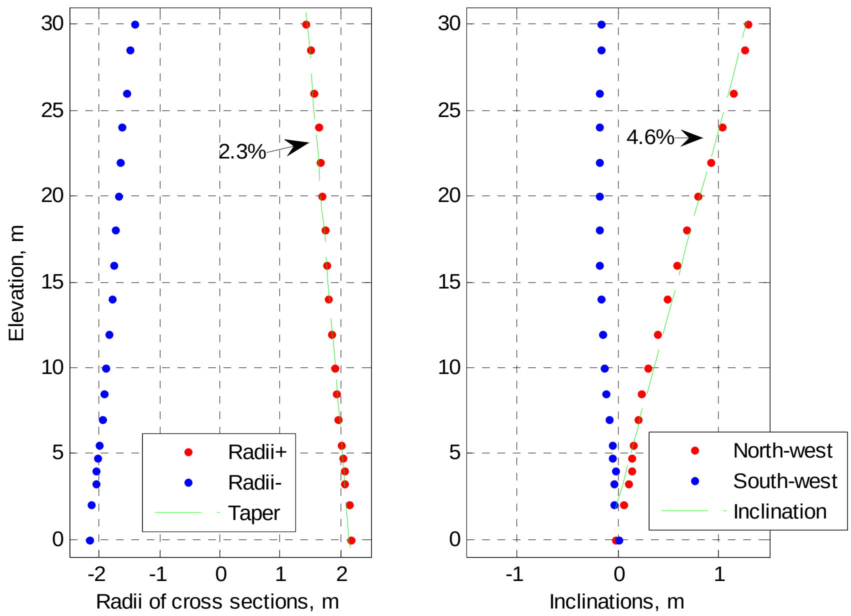


Fig. 22. Taper and inclination estimates of the inclined minaret of the Ulugh Beg Madrasah.

5 DETAILED FE MODELING USING LASER SCANNER POINT CLOUDS

The previous section presented in details some of the different applications for utilizing and manipulating scan data and point clouds generated from the HDS. The presented applications relied primarily on best fitting well-defined geometric shapes and/or solids for different components or parts of scanned structures for possible use in FE modeling or generating accurate geometric surface mesh to capture deformations of the cross sections and construction defects. In this section, scan data is further utilized for a different application or extension to previous applications. This application focuses on generating accurate and detailed 3D structural FE models that can be used for structural and seismic analysis and assessment of historical buildings. Currently, the FE method is extensively used for analyzing new or existing structures for which geometric models can be reproduced from available structural information (geometrical properties, material properties, boundary conditions, and loading conditions). However, due to the complexity and uniqueness of historical monuments, accurate FE models are challenging to be produced based on data collected from regular measurements techniques or seldom available as-built construction drawings. Therefore, possible use of datasets in the form of 3D point clouds acquired from HDS using laser scanners for FE modeling can be extremely useful for historical monuments condition and structural assessment.

An application for using the collected Registan Square ensemble laser scanning data is one of the first attempts to generate detailed 3D FE models and is presented here. The process of developing the FE model for the north side entrance of the Sher-Dor Madrasah, which is the point cloud shown in Fig. 8, is discussed in this section of the paper. Several software packages are required to start with a point cloud and end up with detailed FE analysis results. In this study, two graphics packages were utilized, namely Cyclone [7] and Rhino 3D [11], along with the general-purpose FE package TNO DIANA [12].

The framework and relevant software used for conducting the FE analysis of historical structures is summarized in Fig. 23. First, the scan data is registered and point cloud is generated using the Leica laser scanner software. The point cloud is then exported to specialized graphics software to connect the point cloud nodes and create a polygon (triangular or quadrilateral) surface mesh. For this purpose, the software Rhino3D [11] was utilized not only to create the surface mesh, but also to create additional meshes of reduced sizes for more computationally efficient FE simulations. Typically, the point cloud is a result of a detailed HDS of a 1 mm resolution, which generates millions of nodes and becomes unsuitable for FE meshes at the structure macro-level. Therefore, a much reduced-size mesh is required to make it possible for the available FE packages and available computing resources to handle the model. It is to be noted that the 1 mm resolution for FE models is not suitable only because it is computationally expensive and the current FE packages cannot usually handle models of millions of nodes yet.

The approximately 310,000 element polygon mesh created for the north side entrance of the Sher-Dor Madrasah from the original point cloud as viewed in Rhino3D is shown in Fig. 24. A reduced size mesh that comprises roughly of 45,000 polygon faces was developed using Rhino3D as shown in Fig. 25. The reduced mesh was exported in an advanced geometry and CAD file type, namely a *.STEP file format for the FE pre-processor software to be able to load the model. The FX+ is a pre- and post-processor that comes with the DIANA FE package and is a powerful tool used to generate FE models and output analysis results. The reduced surface mesh was imported in FX+ for the purpose of developing a detailed FE model using 2D shell elements. A linear elastic material model was used to define the masonry material of the structure and uniform thickness shell elements were used for FE mesh. These approximations of linearity, elasticity, and geometric uniformity are for the purpose of preliminary analyses. Future analyses will include more refined modeling assumptions. The detailed FE created in FX+ and defined boundary conditions for the Sher-Dor Madrasah entrance are shown in Fig. 26. Once the FE model is created, the analysis files are defined through another part of the DIANA package, which is MeshEDIT, and the analysis is run through DIANA as described in steps 4 and 5 in Fig. 23. Finally, the results of the analysis can be viewed through FX+ and different response quantities can be observed according to the conducted analysis type.

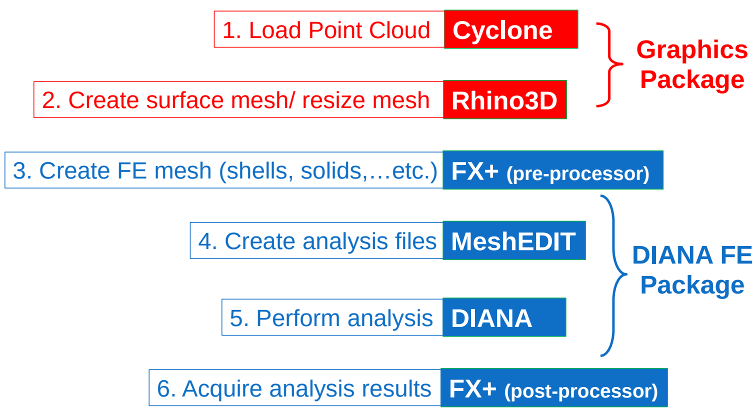


Fig. 23. Summary of the framework to develop FE model and conduct FE analysis from HDS point clouds.

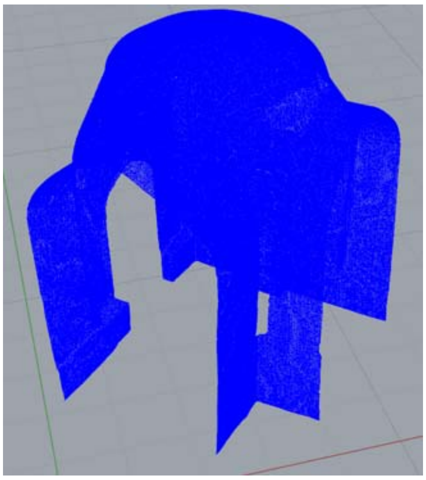


Fig. 24. A dense 310,000 polygon mesh obtained from the original point cloud for the north side entrance to the Sher-Dor Madrasah as viewed in Rhino3D.

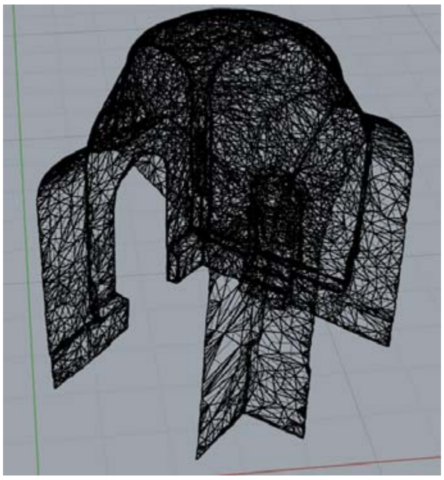


Fig. 25. View of a less dense mesh generated using Rhino3D for the north side entrance to the Sher-Dor Madrasah.

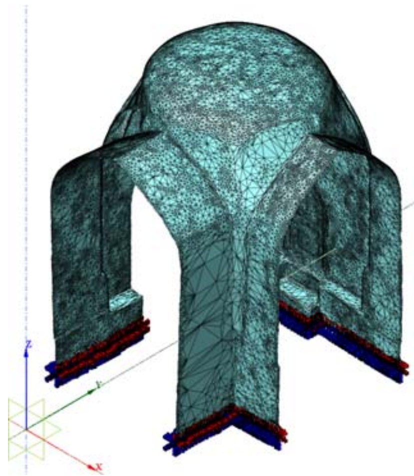


Fig. 26. View of the FE mesh using 2D shell triangular elements generated using FX+ for the north side entrance to the Sher-Dor Madrasah.

Two analyses that utilized the north entrance to the Sher-Dor Madrasah FE model were conducted. Both are linear static analyses under (1) The structure's own weight and (2) Lateral load to identify the lateral stiffness and deformations of this particular part of the structure. The deformed shapes of the structure under gravity load and a lateral load of 2000 kN are shown in Figs. 28 and 29, respectively. A third analysis using the same FE model was conducted for the purpose of obtaining the eigen-solution to find the modes of vibration and natural frequencies of this part of the Sher-Dor Madrasah entrance. The eigenvalue analysis is necessary before a meaningful dynamic analysis or seismic assessment because of the indispensable insight it provides about the dynamic properties of the vibrating system. Two of the vibration modes for the developed FE model are shown in Fig. 29. A larger model for the entrance along with the adjacent and connected structures is required for proper representation of the dynamic interaction and properties. However, as mentioned above, this part of the entrance model is an illustrative example.

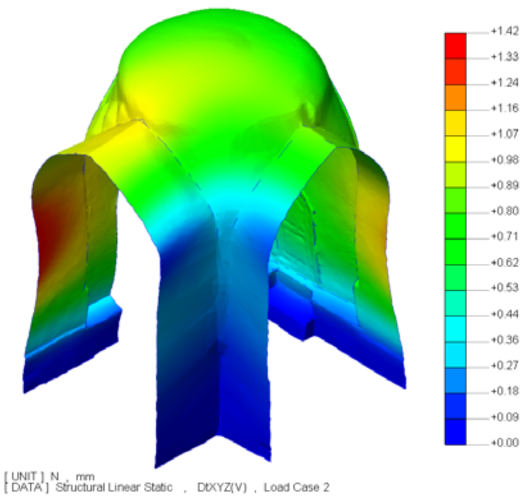


Fig. 27. Deformed shape of FE model for the north entrance of the Sher-Dor Madrasah from DIANA under gravity load [units: mm].

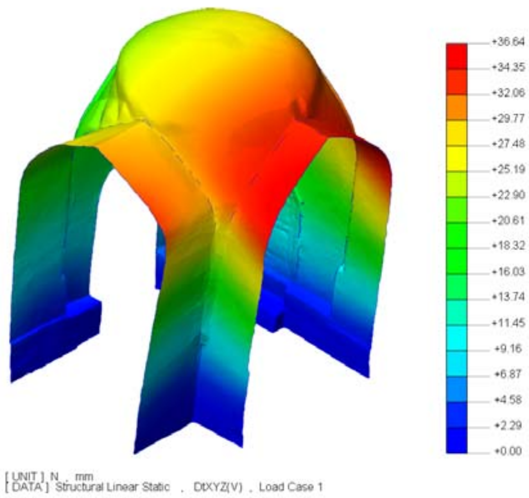


Fig. 28. Deformed shape of the FE model for the north entrance of the Sher-Dor Madrasah from DIANA under lateral load [units: mm].

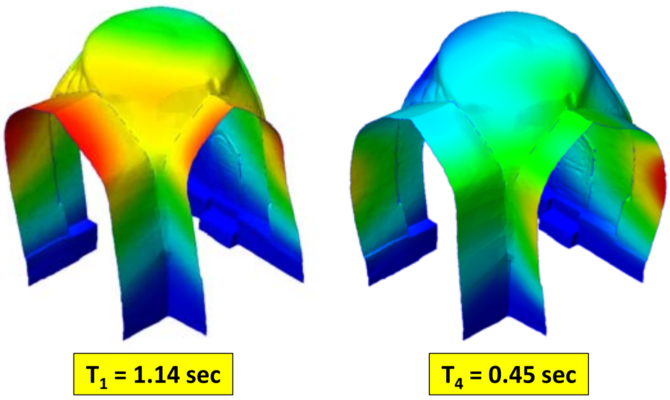


Fig. 29. Two mode shapes from the DIANA eigen-solution of the FE model using 2D shell triangular elements post-processed using FX+ for the north entrance to the Sher-Dor Madrasah.

Although simple linear elastic model and shell elements were used in the previously discussed FE analysis, yet a powerful general-purpose FE package, e.g. DIANA, can be utilized to define a variety of nonlinear material and geometrical models and more accurate solid element types. Defining accurate material properties, especially for nonlinear constitutive models, for historical masonry buildings and monuments is still a challenging task. However, the accurate geometric modeling and FE meshing of irregular shapes and unique geometries of historical structures is a bigger challenge. The examples shown in this study demonstrate that using point clouds can be an excellent way to generate very detailed models for better structural and seismic assessment of historical buildings. There is a great potential in extending the preliminary framework proposed in this study for using point clouds for FE mesh generation to more advanced nonlinear and dynamic FE analyses.

6 FIELD INVESTIGATIONS OF HISTORICAL BUILDINGS IN THE AFTERMATH OF 2014 SOUTH NAPA EARTHQUAKE

A number of churches were damaged during the 2014 South Napa earthquake. Three churches were studied by means of laser scanning. As a representative example, an ensemble of First United Methodist Church in downtown Napa, California, USA, was studied and presented in this paper. The ensemble consists of three adjacent buildings: A) Church's main sanctuary building (1917), B) Centennial hall (1952), and C) Educational building (1955) as identified in Fig. 30.

The research team arrived at the site within several hours after the main shock and scanned the ensemble from 4 positions (stations). It was discovered that the east wall of the church's main sanctuary building (building A) separated from the roof on top and bowed out towards the nearby street as presented in Fig. 31. Since no damages were observed in other buildings of the ensemble, the research team focused their investigation on this unreinforced masonry building only. The views of the wall before and after the earthquake are presented in Fig. 32.

To assess the residual deformations of the east wall and monitor its condition after the aftershocks, several scans of the church were conducted. On the day of the earthquake, the church was scanned from 4 corners to obtain a complete geometry of the structure. On the following day, in about 24 hours after the main shock, two more scans of the church were conducted from the street on the east side of the building. Fig. 33 shows the residual deformation of the east wall where the color of a point in the point cloud depends on the distance from a vertical plane. The arrows show the locations of visible cracks observed in the wall. Fig. 34

shows the vertical slice of the east wall right after the main shock of the earthquake and that after several aftershocks that took place within 24 hours.

Fig. 30. Google Earth view of First United Methodist church ensemble, Napa.

Fig. 31. Ground elevation views of the separation of the east wall of First United Methodist church ensemble, Napa.

Fig. 32. East side wall before (left) and after (right) of First United Methodist church ensemble, Napa.

The comparison of the vertical slices before and after the aftershocks leads to a conclusion that the aftershocks were not strong enough to change the wall's residual deformation caused by the main shock. Depending on future shaking, the situation can change dramatically where the wall can fall on the east side street. Nevertheless, due to the high hazard for passing by traffic and pedestrians, the building was fenced out by a tape right after the earthquake and it was red tagged on the following day.

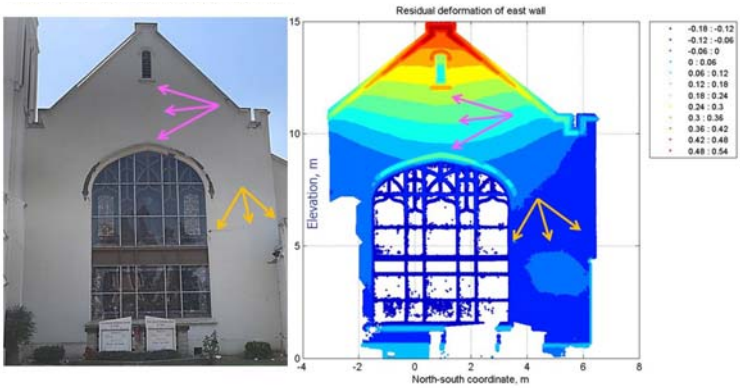


Fig. 33. Residual deformations and cracks of east wall of First United Methodist church main building, Napa: photograph (left); point cloud (right).

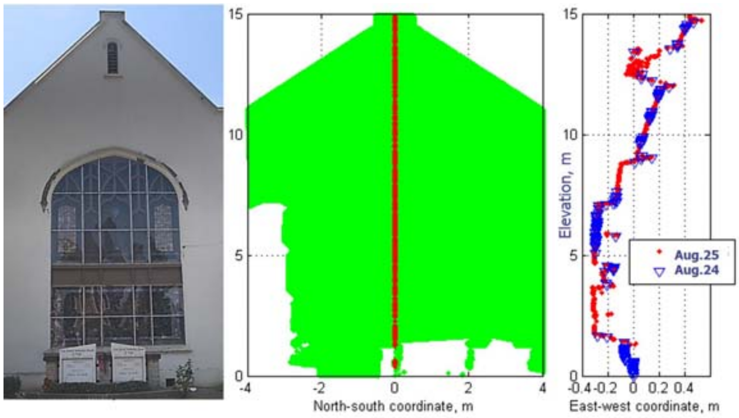


Fig. 34. Laser scans of First United Methodist church main building, Napa, after the main shock and the aftershocks indicating no failure progression.

7 CONCLUSIONS

The paper presents a comprehensive approach to the structural assessment of historic buildings and monuments through the means of laser scanning. The choices of mesh generation techniques have been enriched by a Matlab-based package that uses a point cloud for a regular meshing. The approximate best-fit geometry used in preliminary finite element (FE) models closely represents the as-found geometry of the historic monuments. A new framework was proposed and used in this study to generate detailed 3D FE meshes and models from 3D laser scanning point clouds. It was shown that FE models generated directly from point clouds can be used for better structural and seismic assessment of historical buildings. More detailed future nonlinear and dynamic analyses to be conducted in the next phase of this study are expected to reveal the shortcomings of structural and seismic performances of the historical buildings and monuments.

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