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Reconstruction and rehabilitation of the Grand Al-Nouri Mosque dated to the twelfth century: a case of study

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Abstract

This paper aims to present the structural design and the rehabilitation process as well as the site assessment of the reconstruction and rehabilitation of the twelfth-century Grand Al-Nouri Mosque in Al-Nouri Complex, which is a part of the project Revive the Spirit of Mosul in Iraq. UNESCO launched the project Revive the Spirit of Mosul in February 2018 in order to reconstruct the old city after the destruction and looting from the wars with ISIS (Daesh) in 2017. Al-Nouri Complex includes the Great Al-Nouri Mosque and the 45-m-high Al-Hadba Minaret, which are the iconic historic landmarks of the old city of Mosul on the western side of the Tigris River, and it was built by Nur Al-Din Zengi during the twelfth century. Al-Nouri Mosque was reconstructed in 1942 using the original 40 octagonal Moslawi marble columns, and alabaster arches, the mihrab brought from the Ummayad Mosque in Mosul dates back to 956 AD, masonry stones, and a reinforced concrete roof. In this paper, the structural performance of Al-Nouri Mosque has been investigated through site observations, experimental tests, and structural analyses. Due to the several destructive earthquakes recorded around Mosul, a 3D finite element model of the whole mosque using a commercial finite element program has been developed considering the actual material properties and the effect of wind and seismic actions. Generally, the output results of the structural analysis models showed that the obtained compressive stress values did not exceed the compressive strength values defined for the original footing stones and Moslawi marble. Also, the recommended rehabilitation methodology was proposed to enhance the structural characteristics of the dome, the original Moslawi marble columns, and the old stone footings under the marble columns.

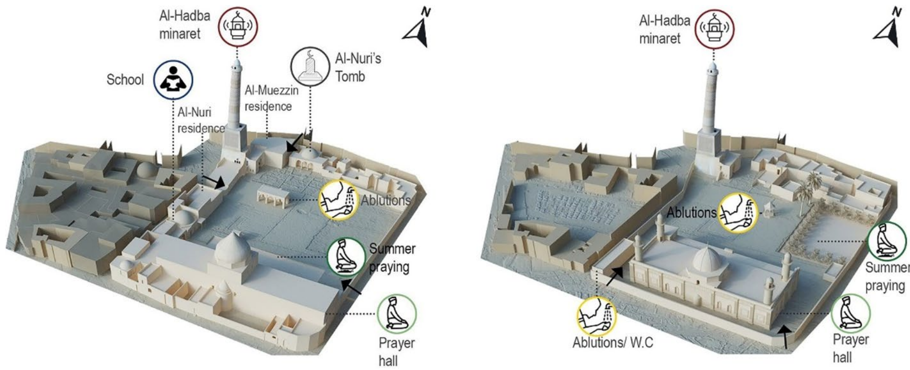
Keywords: Rehabilitation, Site assessment, Heritage, Historical Mosque, Seismic, Spirit of Mosul

Introduction

The Grand Al-Nouri Mosque complex is the iconic historical landmark of the old city of Mosul in Iraq and comprises mainly the Al-Nouri Mosque prayer hall and the 45-m-high Al-Hadba Minaret. It is located at the heart of the old city of Mosul on the western bank of the Tigris River. The Mosque Complex was founded by the Atabeg ruler Nur Al-Din Mahmud Zengi in 1170 AD, and it was exposed to consecutive transformations from the late twelfth century to the second half of the nineteenth century [1]. In 2017, the Al-Nouri Mosque Complex was destroyed due to the explosives placed by ISIS fighters (Daesh) during the last hours before the liberation of the city. The Mosque Complex is defined by tangible and intangible values, categorized into historical, urban-aesthetical, and socio-cultural values. Different studies were conducted and focused on the damage that occurred in the Great Al-Nouri Mosque [1–3]. Khuder [1] analyzed the role of three sites within the heritage framework of northern Iraq and the existing mechanisms for their reconstruction and conservation using three case studies which were Al-Nouri Mosque, Al-Hadba Minaret, and Lalish Temple. This research explored the role of different actors and how these actors had influenced different interpretations of heritage and therefore different responses and approaches to restoration. AlAllaf et al. [3] introduced different solutions for the reconstruction process of Al-Hadba minaret considering the relevant international laws and legislations. Furthermore, Al-Muqdadi and Ahmed [4] applied heritage building information modeling (HBIM) to construct a model to reconstruct the Al-Hadba minaret. This model could provide a lot of useful data such as perspectives, construction drawings, and metadata. The structural assessment of the historical buildings is usually conducted based on the available drawings, site measurements, site observations, numerical methods, and available experimental investigations. Many researchers used these methods to develop the structural assessment of different heritage buildings such as Vuotoet al. [5], Günaydin et al. [6], Bovo et al. [7], Saisi [8], Mustafaraj [9], Demir [10, 11], Halıcı [12], and Pescari et al. [13]. The strengthening of ancient domes and elements using FRP was studied by many researchers such as Al-Saigh and Al-Mahaidi [14], Bloch et al. [15], and Mohamedien et al. [16].

Historical value of the Grand Al-Nouri Mosque complex

The historical significance of the Grand Al-Nouri Mosque complex is due to it was a witness to major chronological developments. For more than eight centuries, Al-Nouri Mosque was and is still considered the principal mosque of Mosul and a prominent feature of the city's skyline and Iraq. It demonstrated Mosul's growth during the Atabeg dynasties; the Al-Nouri complex has preserved its unique location at the core of the old city's market area, as directly chosen by Nur Al-Din to establish the second congregational mosque of Mosul. It is surrounded by a distinctive heterogenic urban fabric dating back to the Late-Ottoman era. Before the twentieth century, the complex impacted the urban pattern, characterized by a system of streets moving from the gates to the Mosque. This system was interlinked with another network heading from the city districts to the river and its southeastern part. The mosque complex had been subjected to frequent changes, but it maintained the main uses that define its character. The twelfth-century mosque complex comprised a prayer hall, a school, and a leaning minaret but with no records about their exact location. Additional buildings were constructed by Sheikh Al-Nouri in the nineteenth century, such as the hospice, the school, his residence, the rectangular ablution, and Al Nuri's tomb. The mosque complex included a green area in front of the prayer hall and was accessed through three gates, as shown in Fig. 1a. Furthermore, a hexagonal-shaped ablution was constructed instead of the rectangular one in 1925, and the eastern part of the courtyard was turned into a garden bordered by fences, as shown in Fig. 1b. Further



(a) (b)

Fig. 1 Uses and entrances of the Grand Al-Nouri Mosque complex. **a** Before 1944. **b** After 1944

(a) (b)

Fig. 2 The Grand Al-Nouri Mosque before reconstruction in the 1940s [1, 20]. **a** The view of the old prayer hall. **b** The front view of the old prayer hall accompanied by the school and courtyard mihrab

interventions were carried out between 1940 and 1950, divided into the demolishment of pre-existing structures, the construction of new ablutions, in addition to the reinforcement of the hexagonal-shaped ablution by adding a new concrete structure around it. Moreover, the courtyard was paved, the garden was modified and enlarged for the summer praying area, and new access points were introduced. Most importantly, the prayer hall was entirely rebuilt with new dimensions and architectural features [17–19].

The twelfth-century mosque prayer hall is not documented, and the design evaluation of the prayer hall reflects its aesthetic assets. In the period between 1211 and 1259 AD, the hall presented a hypostyle structure with Moslawi marble octagonal columns and inscribed capitals. A 16-facetted conical dome was surmounting the Qibla wall, ornamented with stucco. Moreover, a mihrab, built during this period and supposed to have been inside the prayer hall, was moved to the courtyard. Afterward, in 1869, the structure was consolidated with internal walls and additional columns. Also, another mihrab dated to 956 AD was brought from the Ummayyad mosque in Mosul and placed earlier in the west wing. Formerly, the building was composed of two rectangular prisms varying in height; a facetted dome placed on an octagonal form topped the higher prism. The plan layout of the prayer hall was 13 bays in length and 1.50 bays deep. Figure 2 presents the prayer hall before the reconstruction in the

(a) (b)

Fig. 3 The Grand Al-Nouri Mosque [21]. **a** Before 1990. **b** After 1990

(a) (b)

Fig. 4 Interior of the prayer hall in the Grand Al-Nouri Mosque [20]. **a** Octagonal columns with decorated capitals and the Ummayyad mihrab. **b** Mihrab with Lyre capitals in the two wings

1940s. On the other hand, in the period between 1944 and 1950, the new prayer hall presented a different design with a rectangular hypostyle structure with 40 octagonal Moslawi marble columns, as shown in Fig. 3. A dominant hemispherical dome that covers the central bay opposite the mihrab and rested on octagonal and square prisms, respectively. The hall was covered with a flat roof and constructed of stone masonry and reinforced concrete. The preserved elements from the prayer hall were twenty-four octagonal columns with decorated capitals, the mihrab of the Ummayyad Mosque, which was placed in the middle of the Prayer Hall, and four rectangular columns with Lyre capitals, which became columns of the mihrabs in the west and east wings, as shown in Fig. 4. The layout of the building was five bays in length and 1.50 bays deep, with an added portico of another 0.50 bays deep on the northern facade. The octagonal columns supported high pointed alabaster arches and exhibited short friezes on their capitals, previously formed parts of continuous Quranic verses, but mid-twentieth century intervention had disturbed the original sequence. Further decorative elements appeared over the central mihrab, such as a calligraphic cartouche with the inscription for the building's date and patron's name. The entrance inside the hall was made through three semi-circular doors situated on the northern facade, under the portico. The interiors were lit up through a series of semi-circular arched windows with keystones. The northern and southern facades included four windows, while the eastern and western elevations comprised three windows. However, insignificant alterations occurred by the 1990s; the initially simple facades covered by the local limestone (Al-Hillan) with no decorations were later replaced with the same type of stone, but this time with tiles of different dimensions and textures. Pillars representing the interior hypostyle structure enlivened the southern, western, and eastern facades. The same facades were decorated with square panels with circular medallions, containing some of the 99 names of Allah. Horizontal strips of green ceramics and a top strip in stone with Arabic writings from the Quran wrapped around the building from the three sides [1, 17–19].

On the other hand, the Al-Hadba minaret is considered the tallest minaret in Iraq; it is known by locals as al-Hadba, or the hunchback, because of its distinct tilt. Al-Hadba minaret consists of the lower and upper cubical bases, the cylindrical body, and the dome. The upper base and the entire shaft are decorated in typically Iranian brick decoration, basket-weave, and strapwork. Three sides of the base are decorated with a simple stepped pattern, whereas the western side faces the main street and contains an elaborated star pattern. The cylindrical shaft features seven bands of decorative brickwork in complex geometric patterns, followed by a balcony and capped with a white dome [1, 22]. Besides, the creativity of civil engineering is shown by the double spiral staircases that are used to link the inner cylindrical solid core with the outer shell. The freestanding location of the minaret, the extreme height, and the excessive decoration are influenced features from the Iranian Seljuk minarets, which aimed at dominating the urban scape [23]. Karkja [24] presented a full description of the historical value of the Al-Hadba minaret as well as the factors causing the deterioration of the minaret. Figure 5 presents the model to reconstruct virtually Al-Hadba minaret using the heritage building information modeling (HBIM) conducted by Al-Muqdadi and Ahmed [4].

Condition assessment and temporary stabilization measures

The Grand Al-Nouri Mosque complex was exceedingly damaged in 2017 after the placement of a series of explosives by ISIS fighters during the last hours before Mosul

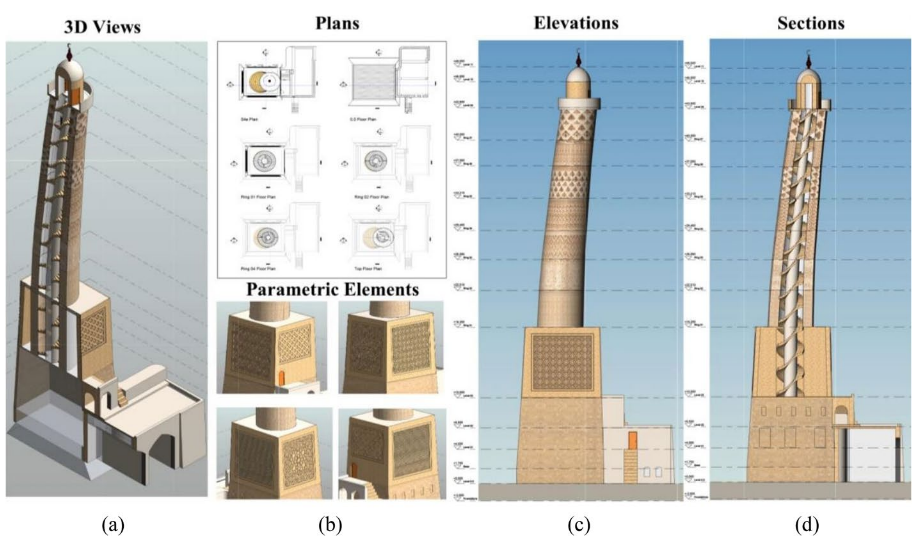


Fig. 5 Al-Hadba Minerate model [4]. **a** 3D view. **b** Plans and parametric elements. **c** Elevation. **d** Section

Fig. 6 The Grand Al-Nouri Mosque after the blasting of the explosive placed by Daesh fighters [25]. **a** The mosque prayer hall. **b** Al-Hadba Minaret

liberation, intended to destroy the complex's two famous landmarks: Al-Nouri Mosque and the Al-Hadba Minaret, as shown in Fig. 6. The minaret lost its entire cylinder-shaped shaft with the lantern and the balcony; only the two bases are still standing. The structure adjacent to the minaret on its eastern side had been exposed to significant fractures across the remaining walls and vaults. Nonetheless, the prayer hall retained only the central dome, parts of the south walls and the Ummayad Mihrab, a few Moslawi marble pillars, and a limited portion of its eastern sector. Part of the surviving structures under the dome appear in a bad state of conservation. The dome's southwestern pillar collapsed, while its other remaining ones are visibly rotated. Furthermore, the western wing, the portico, and all the external walls were destroyed. Extensive losses occurred in the masonry of the octagonal prism, thereby leaving the remaining portions in an unstable situation.

According to the visual site investigation, the current dome is a double dome consisting of two masonry domes: a lower circular dome and a tamped conical upper dome with vertical ribs that are supported on the lower one. The two domes are supported on a ring RC beam, and this beam is placed on the masonry walls above the arches to form the square base of the dome with the qibla wall; at a height of 10 m from the ground, the transition area consisting of muqarnas begins, and these muqarnas have transformed the square shape to an octagon, and the octagonal base is surmounted by a circular base, serrated in shape, on which a stucco-built dome rest. It is decorated, and to protect the inner dome from weather factors, the outer conical dome has constructed the polygon, which is relatively high, is not comparable to any other dome in Mosul, and has 16 faces. It is built with bricks, its height is 15 m, and it is close to the pyramidal shape. In addition, Arches in the prayer hall were built using the local alabaster tiles (Moslawi marble), which is named Alfarsh, to form the arch, and masonry stones were built above these tiles. These arches are supported on the pillars of the mosque which are from local alabaster (Moslawi marble). The damage and the visible defects of the Mihrab, pillars, arches, and domes are summarized in Table 1 and are shown in Figs. 7 and 8. At the end of 2019 and after the war of liberation of Mosul, UNESCO started a project for the execution of safety stabilization measures inside the site of the Al-Nouri Complex which included Al-Nouri Mosque and Al-Hadba Minaret [25], as shown in Fig. 8. This project was conducted using the

Table 1 Condition assessment of the main standing elements of the Grand Al-Nouri Mosque complex

Remaining elements	Condition	Grade Assessment
Al-Nouri Mosque prayer hall		
Upper dome	Minor defect	Fair (minor defect)
Lower dome	Partially cracked may be due to the impact of the explosion	Poor (major damages)
Dome supporting elements (Octagonal prism)	Afflicted by cracks, rotations, displacements, and missing parts	Very poor (critical damages)
RC ring beam	The reinforcement is exposed, the concrete cover is removed, and some major corrosion signs are clear	Poor (major damages)
Arches	Complete or partial loss	Very poor (critical damages)
	Arch base	Very poor (critical damages)
	The space between marble blocks at the crown of the arch is open and it may lead to interrupting the load path mechanism of the arch	Poor (major damages)
	Too many vertical cracks in the masonry above the arches	Poor (major damages)
Moslawi marble pillars	Complete or partial loss	Very poor (critical damages)
	Cracks and lateral movement or sway	Fair (major defect) / Poor (major damages)
Mihrab	In a bad state of conservation, the original decorations are now partially visible after the falling of a large part of the recent plaster overlapped in the middle of the last century	Very poor (critical damages)
Al-Hadba Minaret	Complete or partial loss	Very poor (critical damages)

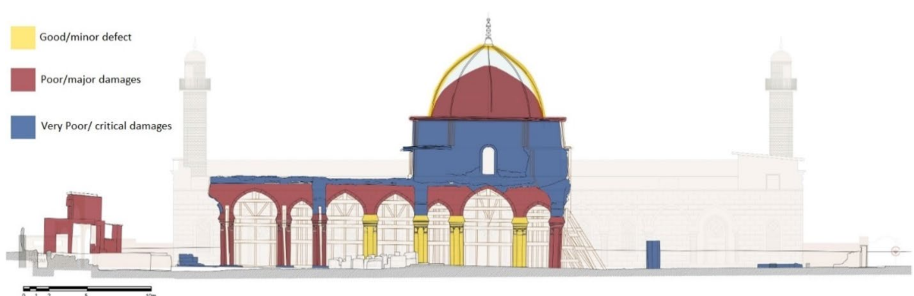


Fig. 7 Illustration of the grand Al-Nouri Mosque complex condition after the war

financial support from United Arab Emirates, in which the paving of the mosque has been cleaned and the position of all the bases of the pillars, whose stone elements have been removed and stored after the preliminary documentation. Additional propping works were conducted to avoid any local collapse of stone blocks due to the powerful blasting. A wooden pillar structure was installed under the Southeast corner of the dome area, the South wall and the Mihrab were shored from the outside, the Moslawi marble pillars were propped from the outside, and all the props were connected to the stone pillars. The old dome of the mosque was temporarily strengthened using polyester stripes, and several wooden props were added to compensate for

Fig. 8 Execution of temporary stabilization measures at the Grand Al-Nouri Mosque complex. **a** The mosque prayer hall. **b** Al-Hadba Minaret. **c** The South wall and the Mihrab. **d** The South-west corner of the dome from outside. **d** The Southeast corner of the dome from inside. **e** The Marble column in Southeast corner under the dome

the missing destroyed stone columns and masonry arches. Also, the reintegration of the masonry in the Mosque was conducted to fill the main gaps.

Reconstruction and rehabilitation of the Al-Nouri Mosque prayer hall

Scales of actions were proposed for the rehabilitation and reconstruction of the Al-Nouri Mosque prayer hall divided into the consolidation and restoration of remaining elements, the reconstruction of destroyed columns, mihrabs, walls, and portico. In addition, new spaces and a re-designed roof were added to meet the current needs, as shown in Fig. 9. The rehabilitation process of the mosque will be conducted as follows:

(a) The mosque prayer hall's remaining elements ought to be restored and consolidated based on the condition of each element, as shown in Fig. 10a.
(b) The reconstruction of the damaged columns, mihrabs, and walls. Moreover, moving forward the arcade to provide Moslawi with an extended summer praying area, as shown in Fig. 10b.
(c) Additional uses are added to meet the new demands. Also, a row of Moslawi columns is appended to define the old portico (riwaq), as shown in Fig. 10c.
(d) The summer praying area ought to be covered with folding sunshades, whereas the mosques' four minarets will be reconstructed on their corners. Openings of the dome are altered to compensate for the prayer hall's raised floor with better lighting, as shown in Fig. 10d.

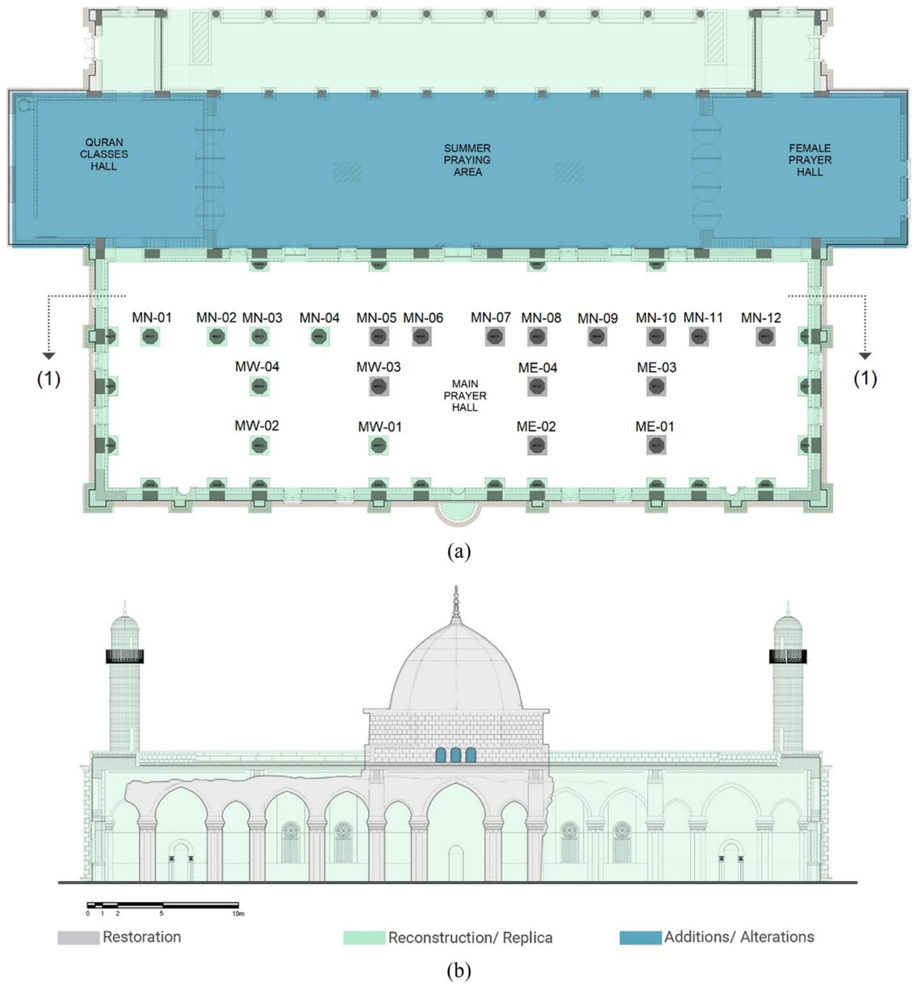


Fig. 9 Illustration of the rehabilitation and reconstruction actions for the grand Al-Nouri Mosque. **a** Plan. **b** Section elevation (1–1)

Structural analyses and design

In order to consider the safety and structural performance evaluations of this historical building, it was investigated by performing a 3D finite element (FE) model using the actual material properties and stresses, which represent the actual condition and deficiencies of the structure, as shown in Fig. 11. The 3D finite element model was developed based on the available drawings, the site measurements, the experimental investigations, and the visual observations during the site visit. The model was developed using the commercial program ETABS v19 [26] to evaluate the behavior of the mosque under the vertical loads considering the effect of wind and seismic actions due to the several destructive earthquakes recorded around the city. This FE model was conducted to assess the global response, stress distributions, and safety of the structure. Also, other commercial finite element programs were used to analyze the different types of the structure such as the structural analysis and design program SAP2000 v20 [27] and the raft and flat plate analysis and design program SAFE v16 [28].

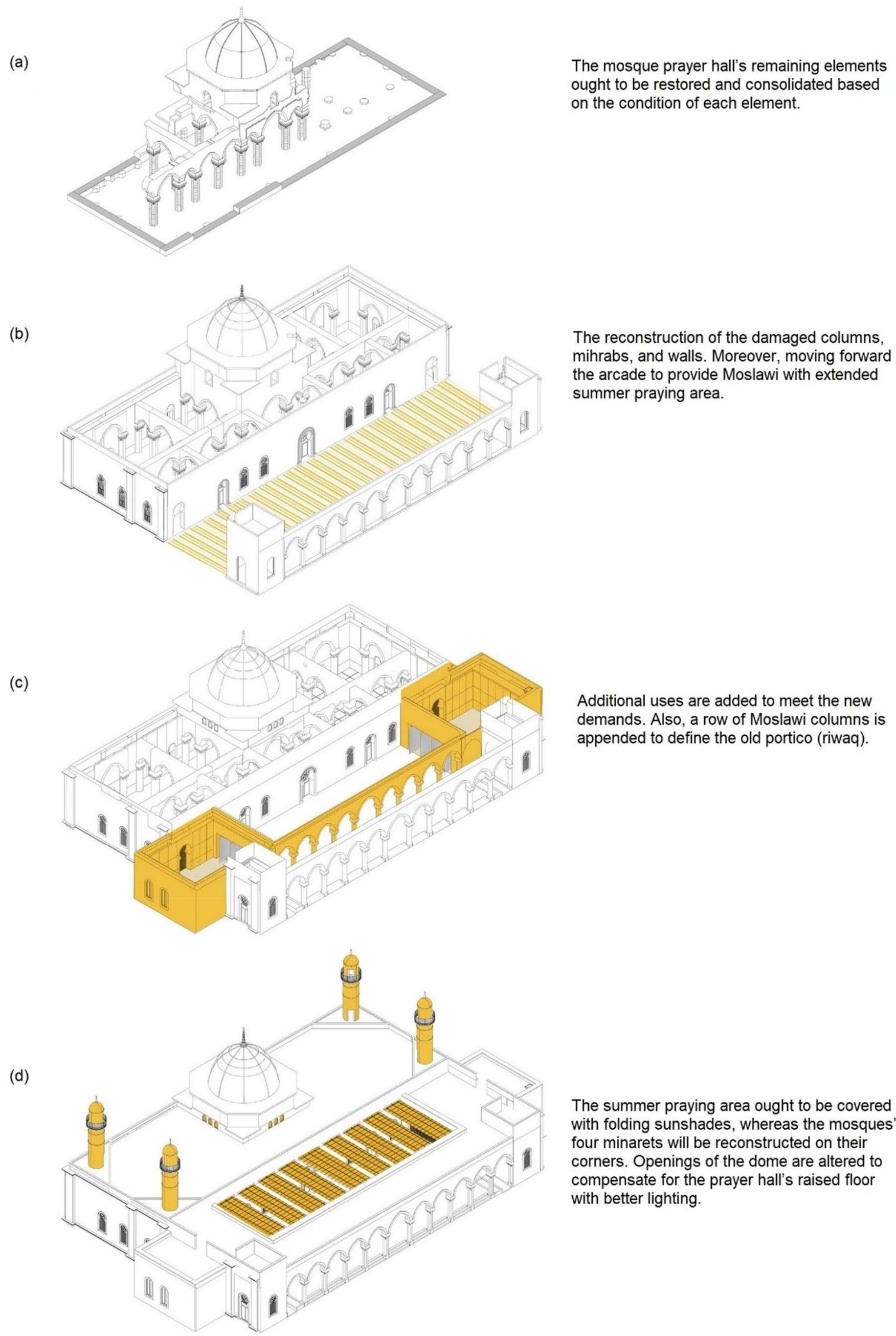


Fig. 10 Rehabilitation and reconstruction process of the Grand Al-Nouri Mosque

In the 3D model, the historical Moslawi marble columns were utilized to support only the vertical loads and it was released of the bending moment at the top and bottom, the reinforced concrete shear walls and columns were utilized to support vertical loads, and the lateral load system depended mainly on the shear walls to resist seismic lateral loads. Also, a reinforced concrete floor was used to cover the mosque similar to the one constructed in 1944. Structural components such as shear

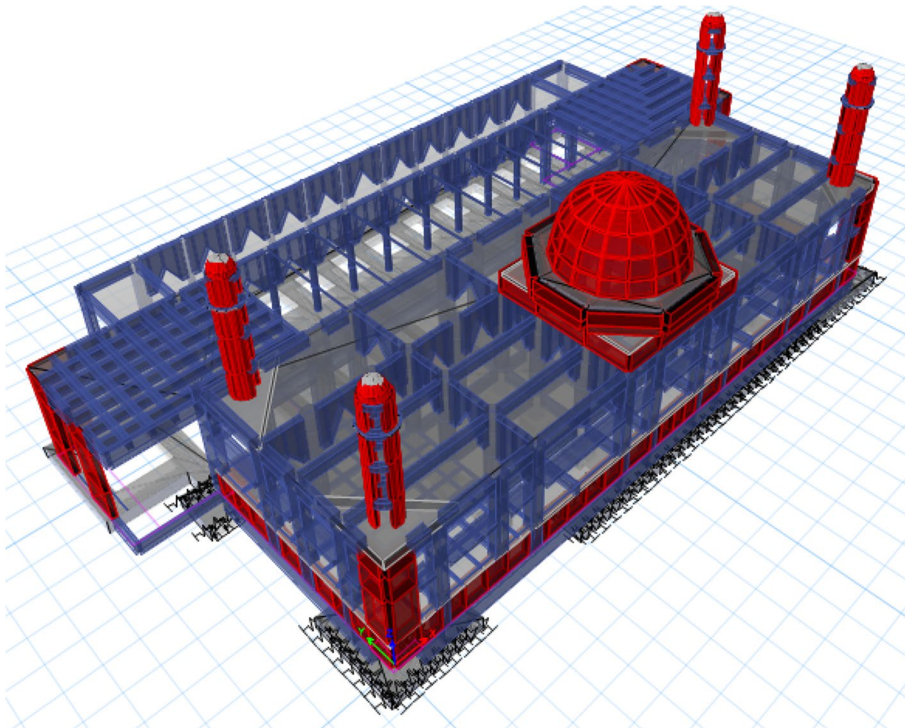


Fig. 11 General view of the 3D finite element model for the grand Al-Nouri Mosque

walls, minarets, and domes were modeled using four-node shell elements with three translational degrees of freedom at each node. While components including Moslawi marble columns, RC columns, and arches were modeled using two-node frame elements.

Another 3D model was prepared for the temporary steel supporting system under the ring beam of the double domes using the program SAP2000 v20 [27], as shown in Fig. 12. This model was used to study the behavior of the double domes under the different loads and also to design the steel members of this supporting system. The domes and the supporting system were modeled using the four-node shell elements and two-node frame elements, respectively. Both of the 3D models were created using the static analysis method for the vertical and wind loads and the response spectrum analysis for the seismic action.

The output results from the different FE models were used to check and design the mosque using the ultimate strength method according to the ACI 318–19 [29] and to satisfy the recommendation of the Iraqi Code for Concrete Structures (304–2011) [30]. The wind loads and the seismic actions were calculated according to the Iraqi Code for Loads and Forces (301–2015) [31] and the Iraqi Seismic Code (303–2013) [32], respectively, and also considering the ASCE 7–05 [33]. In this study, the basic wind speed in Mosul is 40 m/s. For the seismic loads, the importance factor of (1.25) was the nature of occupancy was III and the seismic design category was IV. Also, the soil class was class D. According to the Iraqi contour map of spectral acceleration values of seismic ground motion which was listed in the Iraqi Seismic Code (303–2013) [32], the spectral acceleration at time 0.20 s (Ss) and 1 s (S1) was 1.01 and 0.40, respectively. The long period

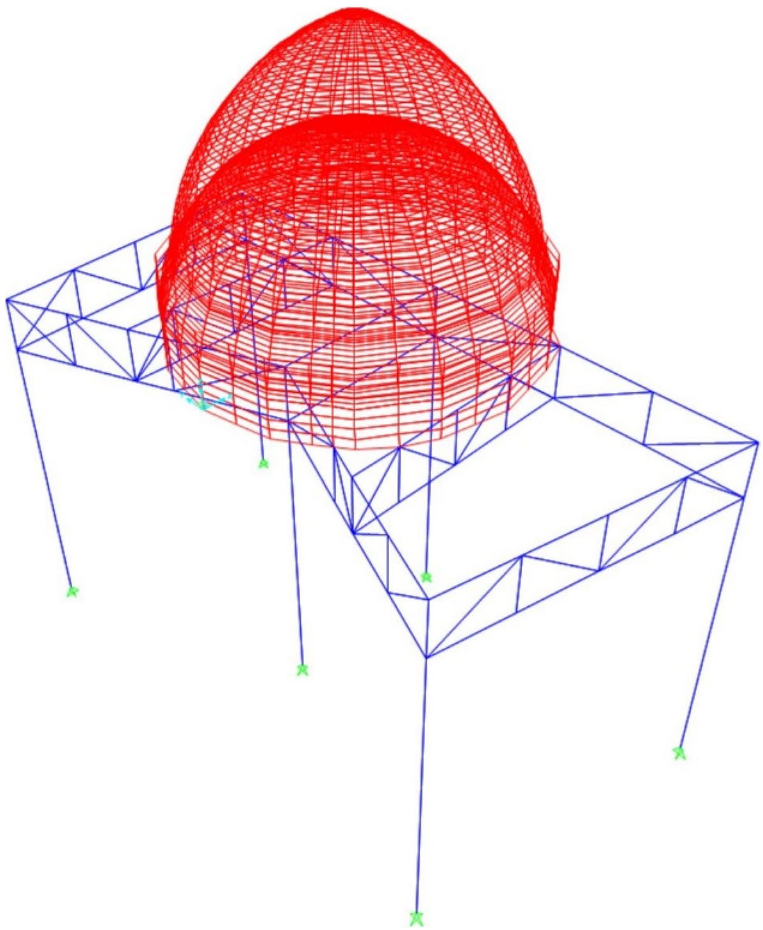


Fig. 12 General view of the 3D FE model for the temporary steel supporting system under the double dome

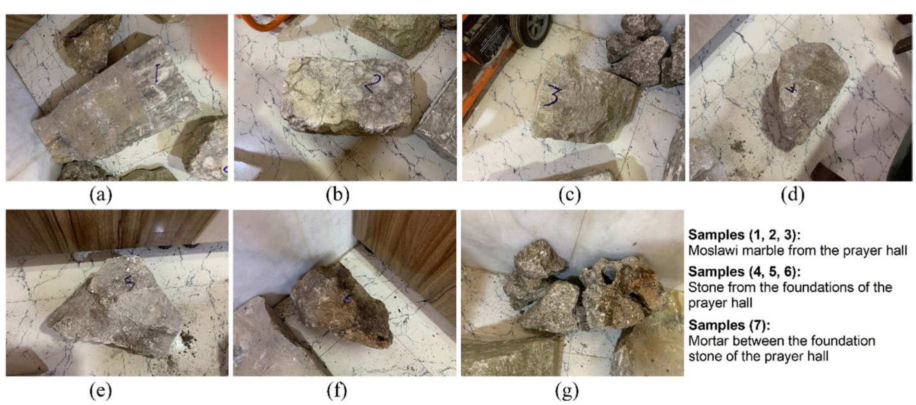


Fig. 13 Tested samples of the old materials used in the construction of the mosque

transition period was 8, the site coefficient (Fa) was 1.096 and the site coefficient (Fv) was 1.60. Mainly, the response spectrum was used with a minimum value of 85% of the equivalent static seismic base shear as per ASCE 7–05 [33].

Materials properties

To evaluate the actual mechanical properties of the original stones and Moslawi marble that will be used in the reconstruction of the mosque, an experimental investigation of these old materials was conducted after getting approval from UNESCO and the Iraqi State Board of Antiquities and Heritage. The original investigated materials included the Moslawi marble used in columns, the stones used in the foundation, and the mortar between the stones of the foundation, as shown in Fig. 13. This experimental investigation was conducted using three samples of each type that was selected from the original damaged parts of the mosque and tested by the Laboratories of Engineering College, University of Mosul, as shown in Figs. 13 and 14. Also, the physical and XRF-minerals experimental tests of the original footing stones and Moslawi marble samples were conducted, as shown in Fig. 14. The flexural test was conducted on specimens with the dimension of 100 × 100 × 400 mm, and the compressive test was applied to specimens with the dimension of 100 × 100 × 200 mm. On the other hand, high-strength stainless steel tie rods and sections with durability characteristics not inferior to those corresponding to AISI 304/316L will be used for the strengthening of the remaining elements such as the Moslawi marble columns and stone foundations. The reinforcement steel bars in the reinforced concrete elements of the new roof and columns were with grades 420/600 and 280/450 for the longitudinal reinforcement and stirrups, respectively. The required compressive strength of concrete (f_{cu}) for the design process was 20 MPa for the plain concrete, 40 MPa for RC columns and shear walls, and 35 MPa for the RC foundations and slabs. To evaluate the mix proportions of the RC concrete elements, a mix design was conducted, and six 150-mm standard concrete cubes for each mixture

Fig. 14 Experimental tests for the samples of the old materials used in the construction of the mosque

Table 2 Mix proportions for the RC elements

Mix	Mix proportions (kg/m^3)						
	Cement	Water	Crushed stone (19mm)	Crushed stone (12mm)	Sand	Superplasticizer (%)	w/c
Plain concrete	300	185	525	525	840	-	0.62
Foundations	400	175	475	475	850	0.70	0.44
Columns	420	162	445	445	850	0.80	0.39
Slab and beams	370	175	465	465	860	0.70	0.47

were prepared and cured. These cubes were tested by the Laboratories of Engineering College, University of Mosul, after 7 and 28 days. Table 2 presents the mixed proportions of the RC concrete elements.

Soil investigation

UNESCO prepared a report presenting a preliminary geotechnical investigation of the subsurface soil at the location of the Al-Nuri Mosque complex. The investigation was built on the results of six boreholes, three of them were drilled around the prayer hall area (MS-1, MS-2, MS-3), and the others (MN-1, MN-2, MN-3) were drilled around the Minaret area. The (MS) boreholes were drilled to a depth of 15 m, whereas the (MN) boreholes were drilled to a depth of 30 m. In addition to the geotechnical investigation, the report was also presenting a preliminary geophysical investigation by conducting a "downhole seismic test" and "GPR survey." The groundwater table was encountered at depth from 7 to 9.80 m below the tops of boreholes, at the time of drilling. Generally, the report was only a factual report providing the subsurface soil properties, and it was considered our unique data source for preparing the foundation recommendations. The general geotechnical and geophysical investigation indicated that the first 15.00 m of the under-surface ground may contain random hidden hollows, as residuals of old structures. Accordingly, the appropriate foundation type is either a rigid reinforced concrete raft on a soil replacement or a rigid reinforced concrete cap on micro-piles. As the locations of the prayer hall were not directly investigated, and the under-ground soil properties were approximated, it was requested to drill at least two confirmation boreholes of depth not less than 20 m before the beginning of the work to confirm the bearing strength and the foundation levels. Also, a propping investigation should be applied before the construction process to investigate the expected hidden voids and cavities that may exist under the working zones.

Results and discussion

The results of the XRF minerals and the physical experimental tests of the original footing stones, Moslawi marble samples, and mortar are listed in Tables 3 and 4, respectively. Accordingly, the dry density of the Moslawi marble was 22.26 kN/m^3 and the dry density of the footing stones was 21.08 kN/m^3. Also, the average dry compressive strengths of the footing stone and the Moslawi marble were 9.36 MPa and 14.36 MPa, respectively, while they were 8.03 MPa and 12.53 MPa for the wet condition, respectively. Similarly, the modulus of rupture of the Moslawi marble was

Table 3 XRF-Minerals experimental test results of the Moslawi marble, stone, and mortar samples

Element	Average test results		
	Moslawi marble	**Footing stone**	**Mortar**
Na_2O	0.31 Wt %	0.00 mg/kg	0.26 Wt %
MgO	0.16 Wt %	0.79 Wt %	0.18 Wt %
Al_2O_3	0.86 Wt %	1.17 Wt %	1.23 Wt %
SiO_2	4.32 Wt %	4.24 Wt %	5.75 Wt %
P_2O_5	0.21 Wt %	0.09 Wt %	0.27 Wt %
SO_3	42.07 Wt %	2.03 Wt %	39.35 Wt %
Ci	0.07 Wt %	0.15 Wt %	0.08 Wt %
K_2O	0.16 Wt %	0.16 Wt %	0.32 Wt %
CaO	51.03 Wt %	90.31 Wt %	50.70 Wt %
TiO_2	0.06 Wt %	0.05 Wt %	0.15 Wt %
Cr_2O_3	50.00 mg/kg	76.00 mg/kg	90.00 mg/kg
Mn_2O_3	80.00 mg/kg	415.00 mg/kg	240.00 mg/kg
Fe_2O_3	0.60 Wt %	0.85 Wt %	1.54 Wt %
ZnO	0.00 mg/kg	0.00 mg/kg	0.00 mg/kg
SrO	0.20 Wt %	0.08 Wt %	0.18 Wt %

Table 4 Physical experimental test results of the Moslawi marble and stone samples

Test	Average test results	
	Moslawi marble	**Footing stone**
Dry density, kN/m^3	22.26	21.08
Compressive strength (dry condition), MPa	14.36	9.36
Compressive strength (wet condition), MPa	12.53	8.03
Modulus of rupture (dry condition), MPa	8.24	2.55
Modulus of rupture (wet condition), MPa	6.19	1.02
Total absorption, %	0.21	8.40
Corrosion, %	1.10	2.18
Rock Permanence, %	98.90	97.82

Table 5 Compressive strength of concrete for the RC elements

Mix	The compressive strength (f_{cu}), MPa	
	at 7 days	**at 28 days**
Plain concrete	25.20	29.00
Foundations	32.60	50.00
Columns	38.60	48.50
Slab and beams	37.00	47.00

8.24 MPa in the dry condition and 6.19 MPa in the wet condition, and the modulus of rupture of the footing stone was 2.55 MPa in the dry condition and 1.02 MPa in the wet condition. In addition, the conclusions of the XRF-mineral analysis of the tested samples showed that the material of the Moslawi marble and mortar contains approximately 50% calcium oxide (lime—CaO) and 40% sulfur trioxide (SO_3). However, the footing stones contained about 90% calcium oxide (CaO) and only 2% sulfur trioxide (SO_3). The silicon dioxide (quartz—SiO_2) in all specimens ranged from 4.24 to 5.75%.

The compressive strength (f_{cu}) results of the different concrete mixtures are listed in Table 5. The actual 7 days compressive strength for the plain concrete, foundations, columns, slab, and beams were 25.20, 32.60, 38.60, and 37 MPa, respectively. Also, the actual 28 days compressive strength for the plain concrete, foundations, columns, slab, and beams were 29, 50, 48.50, and 47 MPa, respectively.

Generally, the obtained results of the structural analyses indicated that under gravitational loads and the effect of wind and seismic actions, the obtained compressive stress values did not exceed the compressive strength values defined for the original footing stones and Moslawi marble. The maximum obtained loads acting on the marble columns from the different types of loading cases are listed in Table 6. Which includes the maximum ultimate loads acting on the marble columns from the vertical loads, the combinations of the vertical loads and the earthquake forces in the X and Y directions, and the combinations of the vertical loads and wind loads in different directions. The marble column numbers are shown in Fig. 9. The maximum load at the columns was at the columns MN-05, MN-06, MN-07, and MN-08 which are located under the dome. The maximum column load was 1827.60 kN, and the maximum compressive stress was 2.21 MPa.

Table 6 Maximum ultimate loads acting on the Moslawi marble columns from the different types of loading cases

Column number	Maximum ultimate load, kN		
	Vertical loads	Vertical loads and earthquake forces	Vertical and wind loads
MN-01	532.87	467.12	434.72
MN-02	547.07	468.09	431.67
MN-03	681.10	587.80	533.18
MN-04	587.15	498.27	460.65
MN-05	1827.57	1424.92	1475.03
MN-06	1095.37	805.14	906.41
MN-07	1073.75	762.82	889.01
MN-08	1773.24	1242.90	1435.29
MN-09	608.22	505.86	476.95
MN-10	682.26	587.52	533.49
MN-11	522.37	453.54	410.29
MN-12	506.97	466.54	414.02
MW-01	251.10	416.32	277.98
MW-02	588.01	481.62	473.92
MW-03	333.20	318.20	282.18
MW-04	843.97	703.58	662.50
ME-01	741.65	625.46	586.24
ME-02	147.67	196.38	191.23
ME-03	767.66	645.07	603.12
ME-04	329.42	228.27	281.58

Rehabilitation methodology proposal

Old double dome

The first recommended rehabilitation methodology is to improve the structural strengthening of the dome by constructing a temporary steel supporting system under the ring beam which was modeled using the program SAP2000 v20 [27]. As loads of the columns are relatively high, pile caps resting on micropiles should be prepared. The horizontal steel trusses will be fixed in place by carefully opening cores using mechanical drills with no vibration mode in the masonry walls. Steel seats will connect the temporary trusses with the ring beams. Anchor bolts will be used to fix the ring beams with the supporting trusses. The concrete cover of the ring beam sides will be removed, and the rust layer of the steel bars will be removed and cleaned using sandblasting. FRP strips will be fixed after restoring the concrete cover. A fiber sheet (FRP) mesh will be fixed to the bottom of the lower dome after injecting any cracks using low viscous epoxy injection, as shown in Fig. 15. Also, the cracks of the upper dome will be injected in the same way. The lower old supporting system including arches, columns, and masonry walls will be removed with special attention. All movements and deformations should be monitored and recorded simultaneously using strain gauges and electromechanical transducers. All the removed parts will be cleaned, numbered, and stored for the rebuilding stage.

Old Moslawi marble columns

In the reconstruction process of the Moslawi marble columns and to increase the ductility of the marble column and to preserve the integrity column, a core with a 50-mm diameter in the middle of the column cross-sectional will be conducted using a water-cooled core-drilling machine with a controlled forward movement. Then, a 25-mm diameter high-strength stainless steel tie threaded rod will be installed inside the core. After that, the marble column core will be injected with a non-cement grout. Also, stainless steel connectors between the marble stones with a diameter of 16 mm and length of 100 mm will be installed using an epoxy resin to prevent the Moslawi marble columns from horizontal separation. The reconstruction details of the marble columns are shown in Fig. 16.

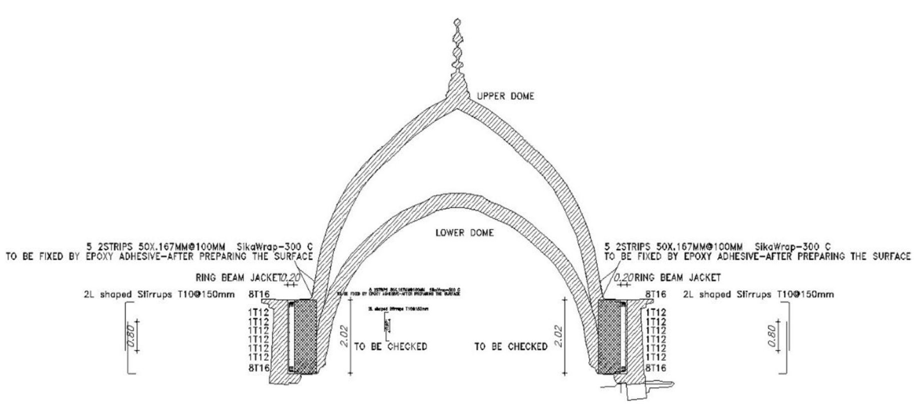


Fig. 15 Section of the mosque double dome strengthening requirements and details

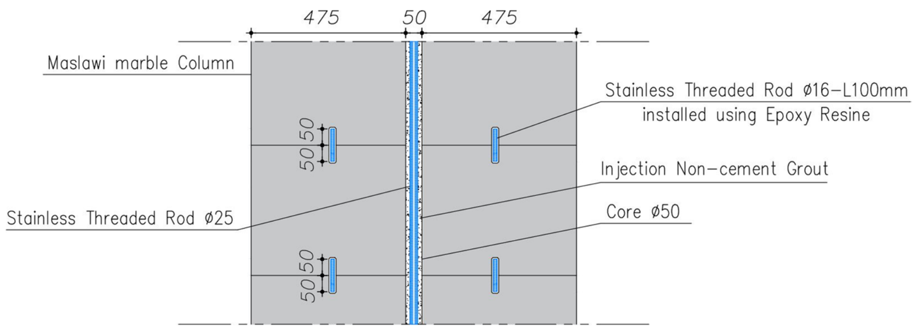


Fig. 16 Strengthening details of the original Moslawi marble columns

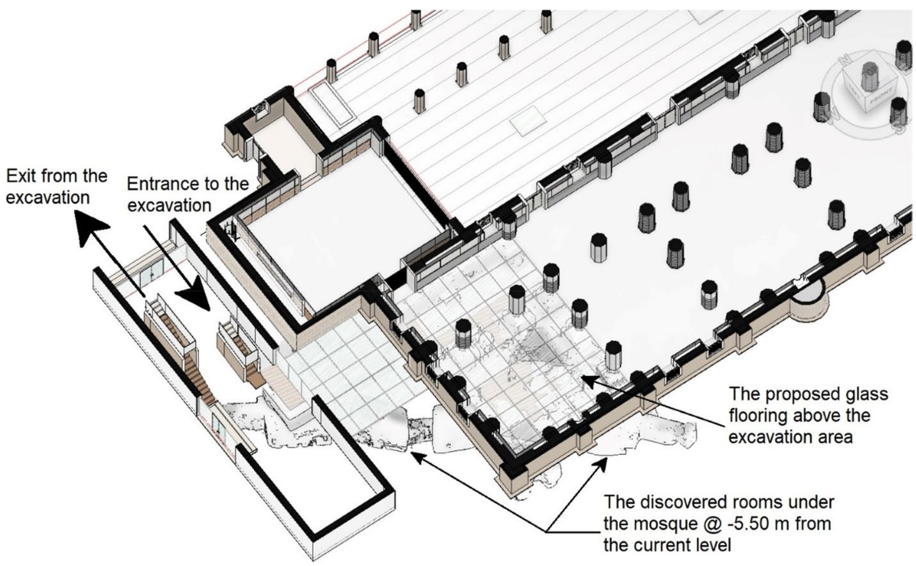


Fig. 17 The original floor of the old mosque and the discovered four rooms below the mosque

Old stone footings

During the archaeological excavation work in the west wing of the mosque conducted by the Iraqi State Board of Antiquities and Heritage inside the mosque, it was discovered that the old Moslawi marble columns were constructed on stone square footings with a height of 1.53 m which was installed on the original mosque strap footing with 1.68-m width. The original flooring of the old mosque has appeared at a depth of 2.0 m below the current level. Also, four connected rooms from stones were found below the mosque at a depth of 5.50 m back to the twelfth century and they were used for ablution with entrance and exit, as shown in Fig. 17 [25]. All these factors make the reconstruction process of the great Al-Nouri Mosque one of the most complex and ambitious reconstruction projects in modern times. Also, it led to making a museum under the west wing of the mosque and the floor of the mosque in this area will be constructed from stainless steel beams and glass.

To prevent any deformations in the old stone footings under the marble columns after the excavation and being uncovered in the museum, it will be confined using stainless steel UPN 200 and 25-mm diameter threaded rods, as shown in Figs. 18 and

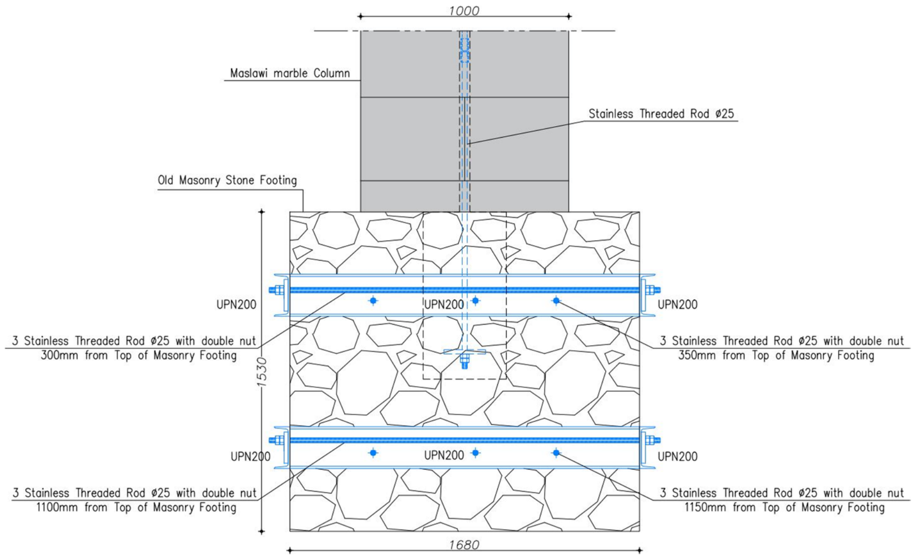


Fig. 18 Strengthening details of the old stone footings under the Moslawi marble columns

19. To ensure the safety of the site, all the testing and exploring available methods have to be conducted before the construction process to ensure the bearing capacity, depth, and integrity of this existing foundation are safe for the column's loads and reactions. In order to study the actual behavior of old stone footing under the marble columns and to ensure its ability to sustain the loads and from the columns safely, a load–displacement test will be conducted before the beginning of work as a sample for one of these footings after applying the proposed confinement and strengthing process.

Conclusions

The main objective of this study was to present the process of restoration and reconstruction of Al-Nouri Mosque dated the twelfth century located in Mosul, Iraq, and to present the structural intervention to preserve the old structural elements. The Grand Al-Nouri Mosque complex was mostly destroyed by ISIS (Daesh) in 2017. The UNESCO organization started a stabilization project in 2019 to preserve the still-existing elements of the mosque and the surrounding area. The reconstruction process of Al-Nouri Mosque is considered one of the most complex and ambitious reconstruction projects in modern times due to the discovered items during archaeological excavation work. In the current study, scales of actions were proposed for the rehabilitation and reconstruction of the Al-Nouri Mosque prayer hall divided into the consolidation and restoration of remaining elements, and the reconstruction of destroyed columns, mihrabs, walls, and portico. In addition, new spaces and a re-designed roof were added to meet the current needs. The work was conducted as follows:

- An evaluation of several elements was presented, and the performance of the Mosque was investigated through the available drawings, the site measurements, the experimental investigations, and the visual observations during the site visits.

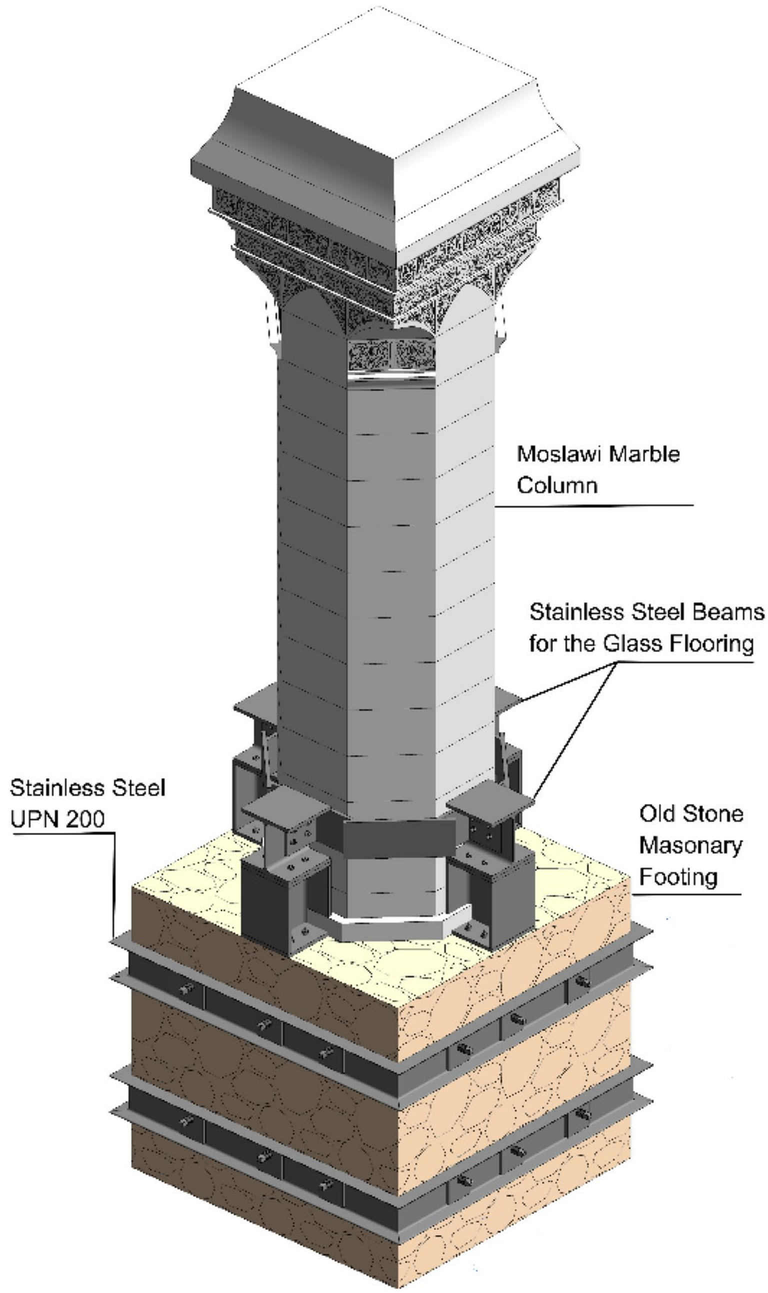


Fig. 19 General 3D model view of the original Moslawi marble columns with strengthening stone masonry footing

- Different experimental tests for the original footing stones, mortar, and Moslawi marble, that will be used in the reconstruction of the mosque, were conducted to evaluate the actual mechanical properties and mineralogical analysis of these old materials. Also, the concrete mix designs were prepared for the required elements and experimentally investigated.
- A 3D finite element model of the mosque was performed using the actual material properties and stresses considering the different vertical loads, wind loads, and seis-

mic actions. The obtained results from the 3D model were used to check and design the mosque according to the required codes and standards. Also, the model was used to ensure that the obtained compressive stress values did not exceed the compressive strength values defined for the original footing stones and Moslawi marble.

- The required proposals for the rehabilitation methodology for the structural assessment of different parts were presented which included the old masonry dome, the original Moslawi marble columns, and the old stone footings under the marble columns.

Abbreviations

3D	Three-dimensional
f_{cu}	Compressive strength
FE	Finite element
FRP	Fiber-reinforced polymers
HBIM	Heritage building information modeling
ISIS	Islamic State of Iraq and Syria (Daesh)
RC	Reinforced concrete
Ss	Spectral acceleration at time 0.20 s
S1	Spectral acceleration at time 1.0 s
UNESCO	United Nations Educational, Scientific, and Culture Organization

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Authors' contributions
MA and SH: conceptualization, methodology, collection of data, literature review, writing, and analysis; AT: conceptualization, supervision, analysis, and revising. The response to the reviewers' comments was prepared by MA and revised by AT. All authors have read and approved the manuscript.

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Declarations

Competing interests
The authors declare that they have no competing interests.

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