Deterioration and Damage Evaluation of the Monument of Qasr al-Bint, Petra-Jordan and a Suggested Conservation Program

Mohamed A. H. Abdel-Halim [1)*] ***and Ziad Al-Saad*** [2)]

[1)] Philadelphia University, Jordan. E-Mail: mshiyab@philadelpia.edu.jo
[2)] Yarmouk University, Jordan. E-Mail: zalsaad@yu.edu.jo

ABSTRACT

Site investigation was made in order to assess and evaluate the existing structural conditions of Qasr al-Bint. The damage and deterioration forms of the structure were mapped and represented by schematic drawings and pictures and their causes were defined. A conservation program is suggested in order to preserve the artistic and historical values of this monument and to strengthen it against any possible earthquake in the future. The conservation program must utilize the same materials and suitable techniques used locally. The program must restore the horizontal diaphragms of the floor over the interior section and the roof of the whole building and ensure that these diaphragms are well interconnected to the walls. The conservation program must provide adequate reinforced concrete tie beams at the middle third of the wall thickness and below the horizontal diaphragms. These tie beams can be arranged in a two-dimensional grid along the wall lines and can be wrapped by polystyrene or isolation sheets to protect the sandstones from any adverse effects that may result from the concrete.

KEYWORDS: Heritage structures, Deterioration, Repair, Cracking, Weathering forms, Conservation, Qasr al-Bint, Petra, Jordan.

INTRODUCTION

Conservation of a heritage structure requires a complete understanding of its structural system, as well as the technology and characteristics of the materials used in its construction. The existing cracks and deterioration forms must be mapped and documented. The nature and extent of the cracks and the material deterioration must be analyzed and their causes identified. Qasr al-Bint monument was the subject of a previous paper (Al-Saad and Abdel-Halim, 2001), which investigated various types of repair mortars that can be used for its structural repair and consolidation. A historical background was given about this monument and previous works which were made to preserve and restore the structure were reported. Archaeological evidence revealed by the archaeological excavations conducted in the monument has shown that Qasr al-Bint was built as a temple during the late Nabatean period, most probably during the reign of Obodas II, 30 B.C.-9 B.C. (Browning, 1982). The exterior of the monument is square looking (32 x 32 m), giving a total ground area of 1024 m^2. Figure (1-a) shows the plan of Qasr al-Bint and Figure (1-b) shows the current view of Qasr al-Bint compared to the original view before damage (Khaldoon Bani-Hani and Samer Barakat, 2006). It is composed of five areas: Portico in Antis, Cella, God-Block or Statue, East Adyton and West Adyton, as shown by the floor plan. There is evidence that both the exterior and the interior of the monument were decorated at one time with hard painted plaster. Qasr al-Bint has been under

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the constant attack of a combination of various environmental factors that resulted in severe damage, deterioration and destruction to the monument. The two most important factors that have contributed to the destruction of the monument are repeated earthquakes and salt crystallization. Qasr al-Bint was rocked by a series of strong earthquake tremors that brought about the monument's collapse. The situation has been exacerbated by weathering damage caused by other environmental factors, especially salt crystallization and efflorescence, frost action, flash floods and water and wind erosion. Damage and destruction of the monument are manifested in various forms. These mainly include cracking of stones and joints due to structural movements and settlement of large areas of the structure in addition to spalling, scaling, softening, etching and distortion of the stones. Evaluation of damage and deterioration of the monument of Qasr al-Bint, Petra-Jordan and the methods which can be used for the protection of Jordan's architectural heritage from the threats of earthquakes and other destructive actions were among the main components of a national research project (Building Research Center, Royal Scientific Society, Amman-Jordan, 1996). Qasr al-Bint that represents a typical example of monuments that have been badly pounded by natural causes was selected for the purpose of this project. This paper presents the results obtained for the second phase of the project, that focuses on the analysis of the mortars, materials as well as systems of Qasr al-Bint. Analysis of the environmental factors which contributed to its deterioration and documentation of the existing physical condition of Qasr al-Bint were also among the objectives of this project. Conservation provisions should be taken only after identification of the deterioration process in order to reduce the risks that the action taken may cause. Actions taken without identification and analysis of the causes of damage and deterioration may become useless or even damaging on the long run. Assessing the structural conditions of an existing historical structure may be a difficult problem depending on the type and extent of damage. Even more complex in many cases is the identification of the cause of damage, which is essential to the development of an appropriate plan of actions for its conservation. The basic objective is to arrive at a course of actions that will reestablish structural adequacy and eliminate or minimize the causes of existing damage without creating new hazards.

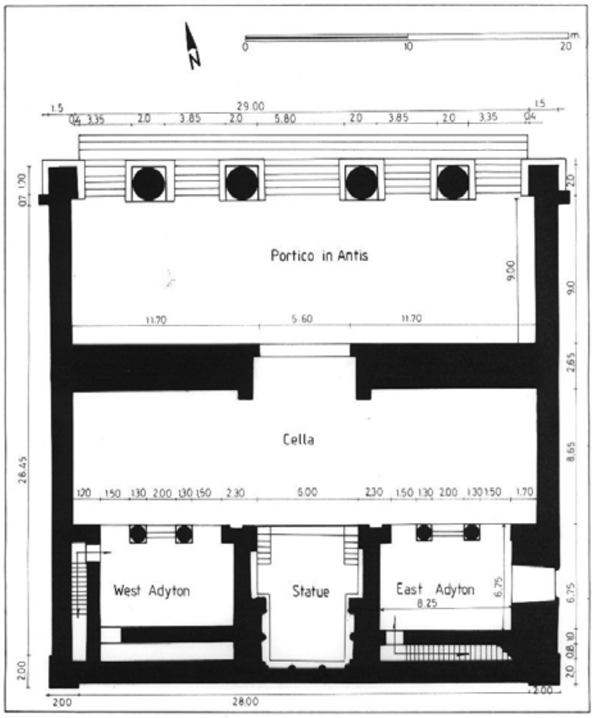

Figure (1-a): Plan of Qasr al-Bint

CAUSES OF DAMAGE AND DETERIORATION OF QASR AL-BINT

During their lifetime, structures are subjected to certain actions that cause damage and others that cause deterioration. Structural damage occurs as a result of numerous events. Earthquakes, floods, foundation settlement, fires, wind, abrasion and overload are only some of the more common causes of damage. There are numerous forms of deterioration that influence the structure's integrity and serviceability and that will ultimately generate a demand for its restoration. The more common forms of deterioration are: scaling, leaching, surface pop outs, chemical reactions, joint deterioration and cracking. These mechanisms, working either independently or in concert, are capable of impairing structural elements or rendering them unserviceable. The deterioration process is generally slower than those factors that cause damages to structures. Deterioration is also harder to evaluate and correct, because it often evolves in stages, over long periods of service. The effects of deterioration and the most appropriate remedial actions need to be characterized and fully evaluated by experts and researchers. One significant difference between deterioration and damage is that deterioration represents a process that occurs over time, influenced by a number of variables. Damage tends to be caused by a specific event. The factors that affect damage tend to be static and once the cause and effect are evaluated, the appropriate corrective action can be applied. Deterioration, on the other hand, involves a process capable of creating ongoing problems. Restoration engineering is complicated as a result of the interaction of damage with deterioration. The problems of stone decay are complex and have been extensively studied internationally for over a half of a century. There are many ubiquitous symptoms of weathering, deterioration and decay. The effects and causes may be listed in two main categories. The first damage category includes cracking of stone and joints due to structural movements and settlement of large areas of the structure. The second category is associated with weathering initiated by the attack of the surrounding environment. This includes cracking, spalling, scaling, softening, etching and distortion of the stone due to a combination of factors like frost action, attack by pollutants, effect of rain and running water, flash flood damage, salt crystallization, among others. The two most important factors that contributed to the destruction of Qasr al-Bint monument are repeated earthquakes and salt crystallization (Amoroso and Fassina, 1983; Honeyborne, 1990).

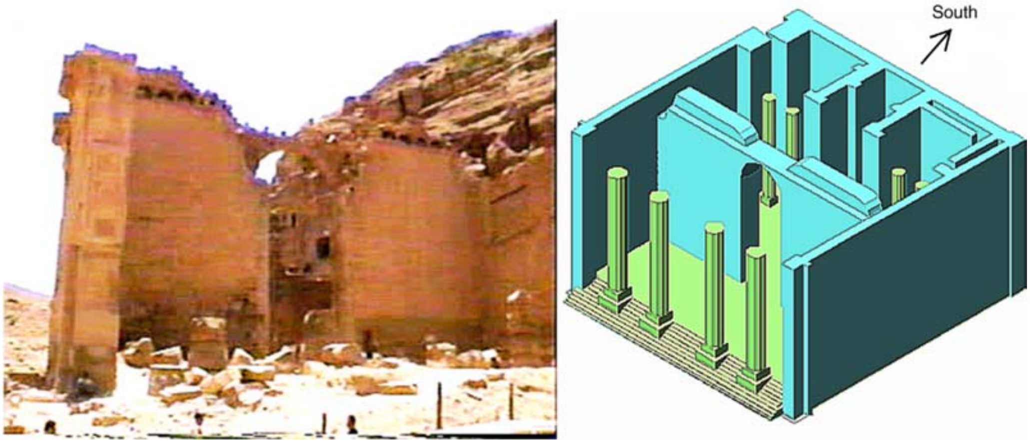

Figure (1-b): The current view of Qasr al-Bint compared to the original view before damage (Khaldoon Bani-Hani and Samer Barakat, 2006)

The Seismic Impact: The Jordan-Dead Sea transform contains two major faults running south north. The first is the Wadi Araba fault with 186 km length and 10 km depth. The seismic slip for each of the two faults is around 0.58 cm/year. This seismic slip has resulted in numerous earthquakes since antiquities that varied in intensity, with maximum magnitude being estimated at 7.3 on the Richter scale. A rough indication of the frequency of occurrence of major earthquakes can be stated simply: one earthquake with a magnitude above 6 occurred every 100 years. It is significant to note that Petra is almost on the Wadi Araba fault and thus has endured in its proximity. The earthquakes reported within about 100 km radius of Petra and that have magnitudes larger than 6 on Richter scale are summarized in Table 1.

Table 1. Historical earthquakes that hit Petra-Jordan

Eq. No.	Date	Latitude (N)	Longitude (E)	Magnitude	Distance to Petra (km)
1	1050BC	30.5	35.3	6.2	24
2	9BC-50AD	30.0	35.3	6.2	34
3	233AD	31.3	35.3	6.3	110
4	362AD	31.3	35.6	6.4	112
5	1460AD	31.0	35.6	6.1	79
6	1834AD	31.2	35.7	6.3	103

NOTE: Petra is on 30.3 N latitude and 35.4 E longitude.

It is likely that the second earthquake in the list shown in Table 1 occurred before the construction of Qasr al-Bint. It is also likely that due to its occurrence in such a close period to that of the construction of Petra, the experience of earthquake damage may have enhanced the skills of the builders of that time. The first earthquakes that could have damaged the monument are those of 233 AD and 362 AD, of which the latter is thought to have been the more damaging, although the above date shows that the 362 AD earthquake is only slightly stronger than that of 233 AD and both had almost the same epicenter. Other factors may have contributed to the survival of the temple, such as the type of mortar which did not decay significantly over that period between the quakes. Also, wood blanks along the horizontal courses may have worked as shock absorbents during the earthquakes. Judging by the condition of the building today, it is logical to assume that progressive failures would have taken place during the many severe earthquakes that occurred after that (UNESCO, 1992).

Salt Crystallization: Salt crystallization can take place in all stones and mortars irrespective of their chemical composition and relatively independently of the surrounding environment. A salt solution transferred to the pores of the stone will, when water evaporates, deposit the salts on the surface of the stone (efflorescence) or within its pores (crytoflorescence) or in both. Repeated wetting and drying cycles lead to re-dissolving and recrystallization of the salts, exerting pressure on the walls of the pores. When this pressure exceeds the internal strength of the stone, there will be a damage in the form of powdering and fragmentation. Efflorescence played an important role in the decay of the monuments of Petra in general and in Qasr al-Bint particularly. This is mainly due to the natural salinity of the Petra sandstone and probably due, to some extent, to salts carried by the wind from the Dead Sea (Torraca, 1988). The damage state of natural stone buildings can be recorded by various methods and with different degrees of precision. The weathered state of a natural building is determined according to type, intensity and extent of the sustained damage and deterioration. Here, the word "weathering" will be used to represent the damage and deterioration status of any part of the structure. There are two levels of the classification schemes of weathering. These are the general classification scheme and the detailed classification scheme. When the weathering state is to be recorded with a high level of precision, the detailed scheme, that is a highly differentiated classification scheme, is required. When applying the detailed mapping mode, all occurring individual weathering forms, their combinations and intensities are recorded. The preliminary evaluation of the weathering state of Qasr al-Bint has shown that different types of weathering forms can be observed. The situation is quite complex. This is because more than one type of weathering are present at a certain location of the monument. Therefore, the detailed mapping mode was employed in order to obtain a useful weathering map of Qasr al-Bint. The general survey of the monument for weathering evaluation has shown that the following general weathering forms can be observed: 1) Loss of important structural elements, 2) Detachment of stone blocks, 3) Relief, 4) Flakes, 5) Spalling, 6) Exfoliation, 7) Cracks, 8) Soiling, 9) Crust, 10) Salt crust, 11) Salt efflorescence, 12) Biogenic crust, 13) Granular disintegration, 14) Outburst, 15) Loss of binding material and 16) Damage caused by previous conservation treatments. These general categories can be sub-divided into sub-groups in order to define more specifically the possible variations and different extents of the weathering forms. On the basis of the classification of weathering forms, a classification of damage categories has been developed, in which all main and individual weathering forms will be correlated to one of the following five damage categories: I-Very slight damage, II-Slight damage, III-Moderate damage, IV-Severe damage, V-Very severe damage. The range of damage categories for each individual weathering form results from considering different intensities of this weathering form (Vonplehwe-Leisen et al., 1994, Fitzner et al., 1992).

GENERAL MAPPING OF THE EXTERIOR WALLS OF QASR AL-BINT

The Southern Wall: The notations used to represent the different forms of weathering are shown in Figure 2. The distribution of the weathering forms observed on the southern wall is shown in Figure 3. It is quite evident that this wall has suffered from strong shocks caused by successive earthquakes. This has led to the development of major structural cracks propagating and increasing in width from the bottom of the wall upwards. The eastern part of the wall was rebuilt in a restoration campaign in 1961/62 using original sandstone (Zayadine, 1985). Figure 4 shows the south-east corner of Qasr al-Bint which was restored in 1961/62. The sand stones used in this restoration were cut from the parent rock in the same old quarry used in building Qasr al-Bint. The figure shows the vertical movemet which occurred in the southern and eastern walls. This movement varies in magnitude from 10 cm at the bottom of the walls to 30 cm at their tops. The wooden laces inserted in between the stone courses are badly deteriorated, which helped in the dismantling of the wall. The lower part of the southern wall suffers from severe weathering and deterioration. The stone blocks in this part suffer from granular disintegration, outbursts, scales and flakes as shown in Figure 5. The upper part is in a better condition and the stones are covered with thick crust layers. There is a general disintegration and loss of mortar that binds the stones together.

The Eastern Wall: The distribution of the weathering forms observed on this wall is shown in Figure 6. This wall suffers from a series of vertical structural cracks caused by earthquake tremors, as shown in Figure 4. The cracks divided the wall into vertical segments that are free standing without any support. In particular, the upper part of the wall might fall down due to any slight vibration caused by even a very weak earthquake. Major concrete construction was carried out at the lower part of the wall, trying to support the wall. The added concrete elements caused severe damage to the adjacent stones, mainly due to salt efflorescence. In addition, the concrete elements look very odd, which harms and disturbs the aesthetic value of the wall. Major restoration work was done on this wall using cut sandstone. As in the southern wall, the old lower part which was not repaired shows severe weathering and disintegration, mainly caused by capillary water and salt efflorescence.

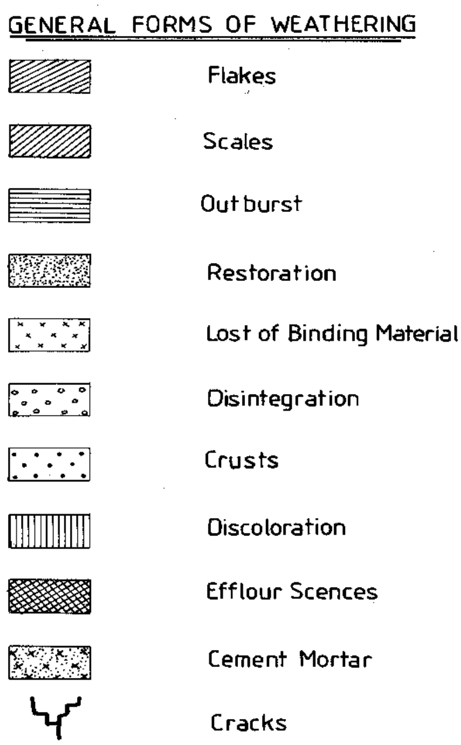

Figure (2): Notations used to represent the different forms of weathering

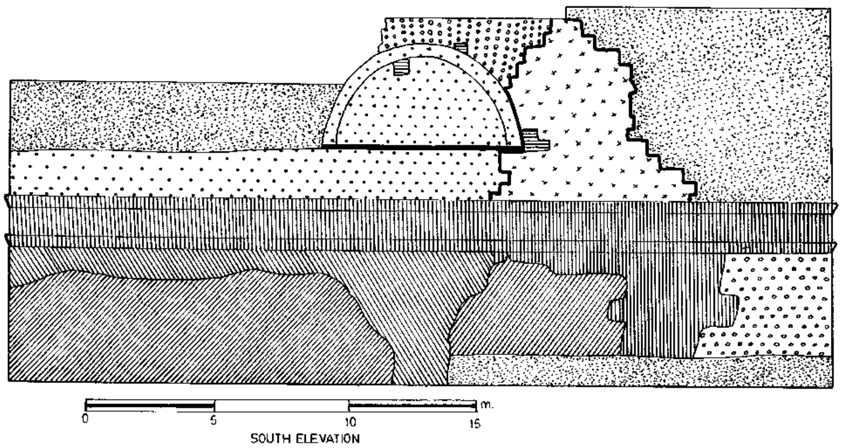

Figure (3): The weathering forms observed on the southern wall

The Western Wall: This is the most preserved wall of Qasr al-Bint. Although there are some structural cracks, they are not as large as those of the southern and eastern walls. Figure 7 shows the weathering forms observed on this wall. Only the lower 2 meters of the wall show extensive weathering. Groundwater, salt crystallization and extensive use of cement mortar in restoration works are the main causes of the extensive weathering of the lower part. The deterioration of that part is manifested by extensive disintegration, outbursts, flaking and scaling.

Figure (4): The south-eastern corner

Figure (5): The lower part of the southern wall

The Northern Wall: As shown in Figure 8, the northern wall suffers from severe shocks and vibrations manifested by extensive structural cracks that cover the façade and penetrate deep into the wall. These cracks represent a real threat to the wall. This danger is quite real and the whole wall may collapse if an earthquake occurs. The upper portions of the wall are almost free standing without any support, which represents a real danger. Similar to the previous walls, the lower part of the wall suffers from bad weathering caused by groundwater and salts, as shown in the picture in Figure (1-b). Different forms of weathering are observed, mainly scaling, flaking and disintegration.

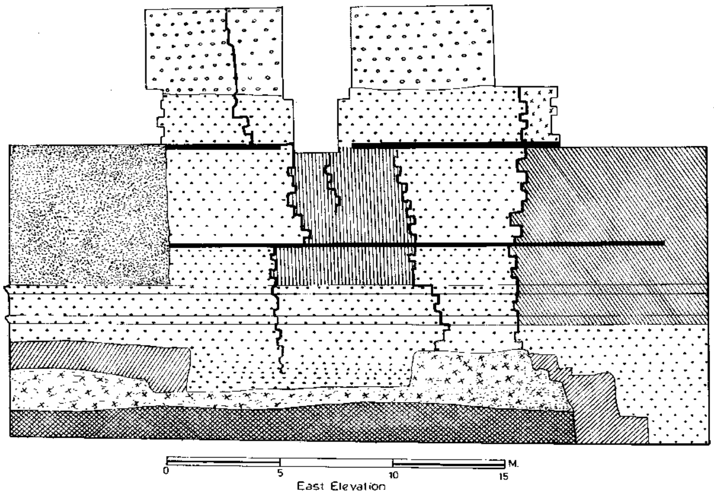

Figure (6): The weathering forms observed on the eastern wall

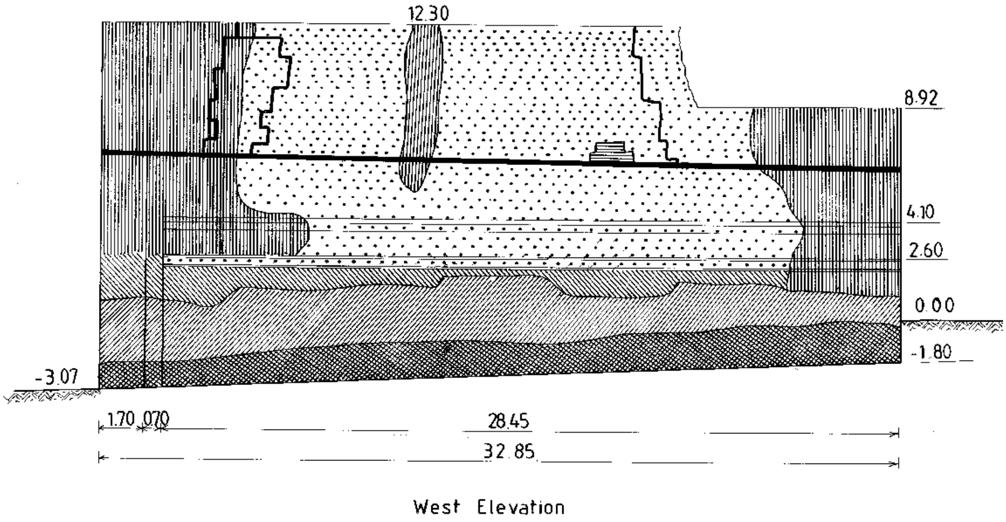

Figure (7): The weathering forms observed on the western wall

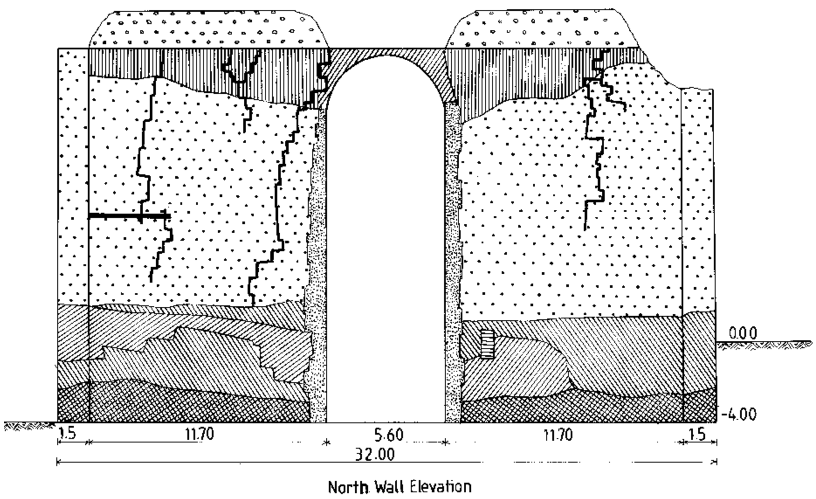

Figure (8): The weathering forms observed on the northern wall

SUGGESTED CONSERVATION PROGRAM FOR QASR AL-BINT

A heritage structure is conserved, because it is believed that it is right to preserve its merits and pass them on to future generations. These merits are represented above all by artistic qualities, but historical and environmental factors also have great importance. In fact, the sensations or effects which can be evoked by a place, building or object must not be ignored. All these aspects must be taken into consideration. This is the basic principle in modern concept of conservation and it is the premise which should guide us through our work. Everything must be done with the aim of repairing and maintaining the original features of the monument without committing an artistic falsehood or erasing evidence of the monument's history.

Materials and Techniques: Only materials and techniques traditionally used by local builders across the centuries must be used for conservation works. Local sandstones from the same old quarry nearby Qasr al-Bint can be used to cut the stones needed. Some of the collapsed stones existing beside the walls and inside the building are still in good condition and can be used in restoring these walls. The same old mortar or the mortars recommended in a previous work (Al-Saad and Abdel-Halim, 2001) can be used for structural repair and consolidation of Qasr al-Bint. Local stone masons are still using the same old technique in cutting, shaping and building stones in different buildings in Jordan. The same building technique can be used to restore the walls of Qasr al-Bint.

Suggested Conservation Works: Qasr al-Bint is a sandstone masonry structure. Such type of structure has insufficient srength, stiffness and ductility to resist lateral loads caused by earthquakes. Qasr al-Bint may undergo various restoration phases. These can be identified as follows.

Repair and Restoration of the Exterior Walls: It is essential to restore the strength and durability of the defective walls, so that adequate safety margins can be achieved. For that purpose, the following steps can be taken to achieve a successful repair.

1. Cleaning the surfaces of walls using compressed air to remove dust, loose sands, fragments,… etc. After complete cleaning, stones that suffered from excessive damage, disintegration or severe cracking must be removed and replaced with sound stones.
2. Repairing all types of crack: Survey revealed different forms of cracking in these walls. These include small structural cracks, large width cracks and voids or very wide cracks. For small and large width cracks, appropriate mortar injection can be used to fill these cracks. Voids or very wide cracks can be filled with Funcosil mortar or any other suitable mortar as recommended by Al- Saad and Abdel-Halim (2001).
3. Walls as well as portions and segments of walls which are beyond repair and suffered from excessive cracking, complete separation (detachment) and vertical splitting, such as the upper portions of the eastern and northern walls, must be removed and rebuilt in the same style using the same sandstones and the appropriate mortar. For misaligned segments, small shifting can be allowed.
4. Large verical cracks and seperations exist at wall intersections and corners. Stone stitching across the crack is one method which can be used to make sufficient interconnection between the walls. Steel tie plates could be used, as another method, to tie seperated wall sections. These plates must be embedded in rich mortar between stone courses and painted or coated with epoxy to resist corrosion.

Repair and Restoration of the Interior Walls: The interior section of Qasr al-Bint includes the West Adyton, East Adyton and Statue. These areas are covered with an intermediate floor. The floor had completely collapsed, but the wood joist holes are still marking the original positions of these joists. The walls of the interior section are badly damaged; however, it is still preserving all the remains of the architectural elements and the information necessary for restoration works. Similar works as for the exterior walls can be done to repair and restore the interior walls.

Construction of Reinforced Concrete Tie Beams: One of the major deficiencies of Qasr al-Bint is the lack of proper horizontal diaphragms and interconnections between these diaphragms and the supporting masonry walls. The structure needs to be tied together along wall lines, in both directions, and at the floor and roof levels to properly survive any future earthquake. After repairing all the walls as explained before and raising them to the floor and roof levels, reinforced concrete tie beams can be used along the walls at the floor and roof levels and in both directions to tie the walls together. These tie beams will also connect the walls and diaphragms together and all these elements with the walls will work together as one unit in resisting lateral forces caused by earthquakes. Since wall thicknesses are very large, the tie beams can be placed in the middle third of the wall at the floor and roof levels as shown in Figure 9. Polystyrene or isolation sheets can be used around the reinforced concrete tie beams to protect the sandstones from any adverse effects that may result from the concrete.

Restoring the Horizontal Diaphragms: The intermediate floor covering the interior section and the roof covering the whole building must be restored at the same levels and using the same traditional materials. Floor construction usually consists of wood boards supported by timber beams or joists.

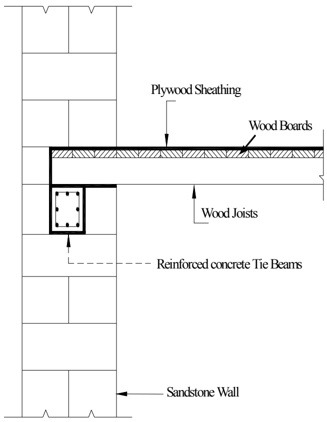

Figure (9): Tie beams positioned in the middle third of the wall thickness

Straight sheathed wood diaphrams of this type are weak for lateral loads. Stiffening and strengthening are often necessary to provide an acceptable diaphragm. Specially manufactured sheathing material, such as plywood, is good for this purpose as an overlayment. It is also possible to stiffen the wooden floor by a thin reinforced concrete slab above the wood construction. A reinforced concrete slab 50 mm thick and reinforced with a steel mesh Φ 8 mm spaced at 200 mm in both directions is suggested; however, this has to be checked by the structural designer and necessary thickness and reinforcement can be used as required by the design calculations. Steel nails can be used to anchor the concrete slab to the wood floor and steel rods to anchor the wood and concrete floor to the supporting walls. Qasr al-Bint is built on sandstone rocks. The wall foundations do not present any problem. There are no sereious settlements or differential settlements between the different parts of the structure.

CONCLUSIONS AND RECOMMENDATIONS

Site investigation was carried out in order to assess and evaluate the existing structural conditions of Qasr al-Bint. The damage and deterioration forms of the structure were mapped and represented by schematic drawings and pictures and their causes were identified. A conservation program is suggested in order to preserve the artistic and historical values of this monument and to strengthen it against any possible earthquake in the future. The following recommendations need to be considered for any conservation program for Qasr al-Bint.

- The conservation program must utilize the same materials and suitable techniques used locally. All cracks must be repaired using the suitable mortar recommended in a previous work (Al-Saad and Abdel-Halim, 2001) and all damaged wall sections must be replaced using sound sandstones available in the place or can be cut from the quarry located in

Petra city near the monument. The conservation program must restore the horizontal diaphragms of the floor over the interior section and the roof of the whole building and ensure that these diaphragms are well interconnected to the walls.

- Adequately reinforced concrete tie beams can be provided at the middle third of the wall thickness and below the horizontal diaphragms. These tie beams can be arranged in a two-dimensional grid along the wall lines and can be wrapped by isolation sheets to protect the sandstones from any adverse effects that may result from the concrete.
- The conservation program must provide good interlocking at wall intersections and corners and connect the horizontal diaphragms to the tie beams to allow the structure to respond as a single unit under the effects of earthquakes.
- Detailed design calculations and construction procedures are needed if these restoration works are to be implemented.

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